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Hydrogel Systems for Gas Channeling and Leakage Control in CO_2 EOR and Storage in Hydrocarbon Reservoirs

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ABSTRACT

Injection of CO_2 into hydrocarbon reservoirs is an attractive method to enhance hydrocarbon recovery and CO_2 storage. However, the non-homogeneity of hydrocarbon reservoirs can lead to low sweep efficiency during CO_2 flooding and leakage during CO_2 storage. This inhomogeneity can be caused by highly permeable matrices and microfractures, which provide channels for CO_2. Gel plugging technology is an effective technique to prevent gas escape and plays an important role in CO_2 flooding and storage. Polymer gel system has good injection ability and can achieve in-depth plugging. Particle gel system has high strength, acid and temperature resistance, and can realize long-term sealing. Foam gel has good injectability and cost advantages, and less damage to the formation. Inorganic gel has good injectability and strong chemical stability. This paper reviewed the research progress and existing problems of four kinds of hydrogels and looked forward to the future development of the CO_2 consistency control gel systems.

Keywords: CO_2-EOR, CO_2 storage, Conformance control, CO_2 leakage, Gel systems

1. INTRODUCTION

The issue of global climate change caused by greenhouse gases is of global concern.CO_2 generated by fossil energy combustion is the main source of greenhouse gases, so it is particularly important to achieve carbon emission reduction [1] CO_2 capture, utilization, and storage (CCUS) is the only technology option to realize low-carbon utilization of fossil energy at present. On the one hand, CO_2-EOR technology can inject CO_2 into the reservoir to achieve resource utilization and improve oil recovery, and on the other hand, it can achieve the purpose of storing carbon dioxide [2,3]. Most of China's oil reservoirs are terrestrial deposits, which have strong heterogeneity and developed microfractures, and CO_2 injected into the reservoir is easy to escape, leading to lower displacement efficiency [4]. In addition, for large-scale CO_2 storage, society always worries about and suspects the potential leakage risk of CO_2 storage. Therefore, it is of great significance to develop CO_2 gas channeling and leakage control technology to secure efficient utilization and safe storage of CO_2 in CCUS-EOR projects.

CO_2 gas channeling and leakage are two different problems: gas channeling refers to the phenomenon that injected gas is produced in a continuous phase, which is the inevitable result of the late stage of CO_2 flooding development. CO_2 gas channeling leads to the ineffective utilization of injected CO_2, exacerbates the contradiction of co_2 flooding development, and at the same time, there is a safety risk of producing a large amount of CO_2 after gas channeling. CO_2 leakage refers to the behavior of CO_2 injected underground escaping through various channels, which is different from the stage of gas channeling. The mechanism and solution of CO_2 gas channeling and leakage are shown in Table 1 [4–7].

Gel systems have been widely used for conformance control and are widely classified. The polymer gel system accounts for the largest proportion. It is mainly injected into the formation in the form of polymer solutions or large blocks to form gel to play a plugging role [8]. The PPG system is a preformed gel system, which swell after absorbing water. PPGs are injected into reservoirs in the form of gel particles

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[9,10]. In addition, the foam gel system generates foam by adding a foaming agent or surfactant, and finally blocks gas channeling or leakage channels in the form of foam, which has the strength property of gel [11]. In addition to the above classification system, inorganic gel is a system with silicate as the main component, which is induced to form gel by pH change [12,13]. Based on this, the gel system is divided into four categories: polymer gel, particle gel, foam gel and inorganic gel. It basically includes all current gel systems, and can comprehensively introduce the plugging performance and injection performance of gel systems.

However, there is currently insufficient research on the control of CO_2 leakage, especially in the case of CO_2 leakage caused by deep fractures or faults. In addition, not all gel systems are suitable for CO_2 consistency control. For example, some gels have dehydration problems in the acidic environment of CO_2 [14]. Therefore, this paper focuses on the gel plugging system that can be used to control CO_2 gas channeling and leakage in the process of CO_2-EOR, combs the performance characteristics and problems of various gel systems, and looks forward to the future development of the CO_2 gel control system.

Table 1. CO_2 gas channeling and leakage mechanism and control method

	Mechanism	*Control method*
CO_2 channeling	• Reservoir heterogeneity • Gravitational segregation (gas overriding) • Viscous fingering due to the low viscosity of CO_2	• water alternating gas injection • CO_2 foam • CO_2 direct thickening gel treatment
CO_2 leakage	• CO_2 leakage along the drilling annulus cement, shaft bridge plug or surrounding rock fracture zone due to chemical and mechanical effects • Large-scale injection of CO_2 can lead to increased formation pressure and changes in stress state, causing previously closed faults and fractures to open or slide, and leading to leakage along faults/fractures • Seepage leakage, diffusion leakage and fissure leakage along the caprock	• suitability of hydraulic barrier • foams treatment • gel treatment • paraffin wax • microcement

2. POLYMER GEL SYSTEMS

Polymer gel is the most widely used type of gel in fluid control research at present. It can absorb water and expand to form a barrier after underground crosslinking, block high permeability fractures or high permeability matrix, and prevent the unorganized flow and leakage of CO_2 in the reservoir.

2.1 Polymer gel formation process

The polymer gel system takes water as the mother liquid, and adds polymer and crosslinker in a certain proportion. Under the stimulation of the initiator, the polymer molecules are cross-linked and gradually form chains. After winding, a three-dimensional grid is formed, that is, a gel with a certain strength. Among them, organic monomers are mainly represented by acrylamide, and crosslinking agents can be divided into metal crosslinking agents, organic crosslinking agents, oxide crosslinking agents, etc. The initiator is mainly represented by persulfates, such as ammonium persulfate and potassium persulfate. In addition to the above components, some additives can also be added to the polymer gel system to play a specific role, thus enhancing the environmental adaptability of the polymer gel system to respond to specific reservoir conditions. According to the type of cross-linking agent, it can be divided into metallic crosslinker polymer gel and organic cross-linking agent polymer gel. In addition, some new polymer gels have been widely used for CO_2 escape control due to environmental and inefficiency

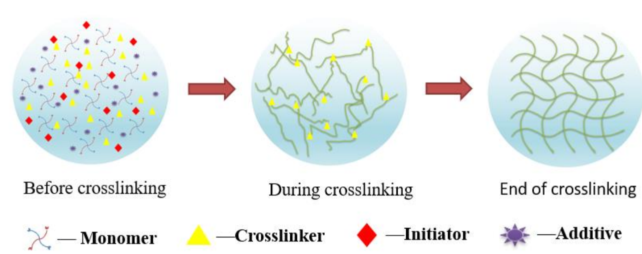

Fig 1. Transaction process polymer gel

issues. The gel process of typical polymer gel is shown in Fig.1.

2.2 Research status of polymer gel

With the gradual rise of CO_2 oil displacement and storage integration in recent years, it is very important to realize the application of polymer gel in CO_2.

As early as the 1970s, Al(III)was used as a crosslinker to synthesize polymer gel, but Al(III)was sensitive to acid and alkali properties, and its cross-linking reaction was too fast. For CO_2 channel plugging, it is only used in the near wellbore area and cannot achieve deep profile control. Cr(VI) has also been discontinued due to its strong carcinogenicity. In recent years, metal crosslinked polymers have shifted from water plugging to gas plugging. The crosslinking agents represented by Cr (III), Zr (IV), and HPAM crosslinked gel systems have become more mature. Sydansk realized the controllable gelling time (several minutes to several weeks) by controlling the concentration of Cr (III). Research by Ashari and Taabbodi suggests that whether there is residual oil or not, Alcoflood 935Cr (III) gel system can effectively reduce the effective permeability of brine and CO_2 in carbonate porous media [14]. Later, by changing the concentration of sodium lactate, it was found that adding sodium lactate could extend the gel time of the gel system. Song et al. developed a new self-healing polymer gel [15]. The self-healing ability is attributed to the combination of pre-embedded Zr(IV) ions and polymer chains.

Compared with the metallic crosslinker gel system, the organic crosslinker gel system has better stability and strength and is an environmentally friendly product [16]. The polymer gel synthesized by traditional PAM has poor acid resistance. In order to adapt to the acidic environment of high-pressure CO_2 in deep reservoirs, M. Raje et al. found that the gel system obtained from phenolic compounds had the highest plugging efficiency for CO_2 and brine, and had good stability [17]. Li et al. developed a CO_2-triggered gel [18]. Before response, the gel solution can maintain a very low concentration to achieve deep injection. When it moves to the CO_2 acid and high temperature environment, methylamine can release formaldehyde (formaldehyde). The released formaldehyde can react with polyacrylamide (PAM) and res-orcinol to generate phenolic resin through condensation polymerization, and the phenolic resin can further react with PAM to generate gel to achieve plugging.

Conventional polymer gels are toxic. Branched polyethyleneimine (PEI) can be used as an organic crosslinker to crosslink with polyacrylamide type polymers to form stable non-flowable gels, which have the advantages of low toxicity and high thermal stability. Yi et al. investigated the gelation process of the PAM/PEI system using the dynamic thickening method, and divided the gelation process into three phases: induction phase, reaction acceleration phase, and equilibrium phase[19]. Muntasheri et al. studied the cross-linking mechanism and thermal stability of the PAM/PEI gel system and found that the gel system could be stable at 130°C for more than 8 weeks [20]. Responsive gels have been more widely used in recent years due to their ability to respond to external stimuli such as temperature, pH, and pressure, but studies have shown that their cross-linked structure is inhomogeneous, resulting in low gel strength and brittleness, which shows that the strength of the chemical cross-linked network limits the development [21]. Cong et al. developed a stretchable self-healing graphene oxide-polymer composite hydrogel with a dual network that exhibits enhanced mechanical properties and self-healing under pH stimulation. In addition to dual network polymer gels, nanocomposite (NC) polymer gels also have better mechanical properties, with tensile strengths up to 10 times that of ordinary gels [22].

3. PARTICLE GEL SYSTEM

The particle gel is usually prepared by cross-linking polyacrylamide or HPAM to form a gel on the ground after cross-linking agent, and then after then granulation, drying, crushing, and sieving processes to gel particle form. Particle gel plays an important role in the process of oilfield development and drive regulation due to its dispersion form in an aqueous solution and good water absorption and swelling [23], which can swell up to several hundred times.

Bai et al. divided the consistency control problems of CO_2 drive in oilfields into two categories of near-well and far-well problems, which were later solved by particle gel systems with different sizes and different expansion rates for the matrix, fracture or frac-ture-like channel problems, respectively [9]. Zhang et al. observed that PPG transported in a piston form in the fracture and formed a gel block after swelling, which visually clarified the morphology of particle gel in the fracture by establishing a transparent fracture model[24]. Abdulmohsin Imqam et al. determined the factors influencing the plugging efficiency of particle gel on the seepage channel by observing the compression morphology of particle gel in the seepage channel under different pressures [25]. Through observation, it was found that the particle gel formed permeable blocks under pressure and did not completely block the channel. Its permeability depended on the strength, particle size, and bearing strength of the gel, which contributed to the design of the particle gel. They also simulated non-homogeneous fractures by designing conduits with different geometries to study their effects on gel transport and showed that the PPG injection pressure increased significantly as the conduits became more inhomogeneous. The particle gel aggregates at the throttling point within each conduit and causes a corresponding increase in injection pressure. The presence of large amounts of CO_2 during the CO_2 drive causes the reservoir to be acidic[26]. To improve the acid resistance of particle gels in a CO_2 environment, Zhou et al. prepared acid-resistant pre-crosslinked gel particles (AR-PPG) by free radical polymerization using acrylamide (AM), N, N'-methylene bisacrylamide (MBA) and dimethyl diallyl ammonium chloride (DMDAAC), which have better swelling and shear resistance in the acidic environment [27]. In addition, some novel materials were applied to the gel synthesis. For example, the particle gel with intelligent response performance is characterized by the good injectivity of the responsive particle gel without significant change in size before response, while the size increases significantly after expansion with better sealing ability. A new type of CO2-responsive preformed gel particles with an interpenetrating network (IPN-PAASP) was synthesized by Pu et al. and evaluated to prove the advantages of the above CO2-responsive particle gel[28]. Hydrophilic nanoparticles can be introduced to have better strength compared to conventional gel particles[29]. In addition, particle gels with higher expansion multiples will have a significant decrease in strength after expansion and are easy to be broken, which will reduce the stability of sealing against CO_2 and may lead to the failure of sealing by new escaping channels. In recent years, a self-healing or re-crosslinking gel system has been applied to solve this problem. Pu et al. studied a new type of re-crosslinkable particle gel (RPPG), which can be re-crosslinked within a certain period. The weak ionic bonds distributed in situ in the gel provide self-healing, toughness, and adhesion for the synthetic core, and the ionic interactions within the gel prompt the re-crosslinking of the particles re-crosslinking of the gels [30].

4. FOAM GEL SYSTEM

Based on the traditional foam plugging system, foam gel system combines foam plugging control and gel plugging control. It is a uniform dispersion system with gel as the continuous phase and gas as the dispersed phase.

4.1 Research progress of foam gel

Romero-Zeron and Kantzas observed the regeneration and remodeling of foam gel after its migration in porous media was destroyed through a visual model [31]. Lai et al. studied the influence of different crude oils on the performance of foam gel. When there are many original polar components (asphaltene and resin), gel foam shows high stability [32]. Research by Romero-Zeron and Kantzas suggests that foam gel has higher sealing efficiency in a strong oil-wet system than in a strong water-wet system, and foam gel has higher sealing efficiency in a low aspect ratio of pore body/pore throat size [33].

The stability of foam gel is the key to its application. As early as 1994, Miller and Fogler developed a model to calculate the critical stable pressure of foam gel[34]. In order to test the stability of foam gel in high temperature and high salt environment, Almaskeen et al . determined the formula of the foam gel system by testing the gelling effect of seven polymers and foaming agents under high salt and high temperature [35]. The core plugging experiment shows that foam gel may not be suitable for blocking fractures. Friedmann et al. developed a foam gel system that can be used in low pH environment[36]. It has a good compressive capacity according to laboratory evaluation, and the field test results show that it has good oil recovery improvement effect, and the cost is 50% lower than the previous gel treatment unit volume.

4.2 Advantages and disadvantages

Compared with pure gas, foam gel has a higher effective viscosity. In addition, foam gel has the advantages of low fluid consumption, low price, high efficiency, and less formation damage, which is suitable for plugging reservoirs with strong fracture and heterogeneity. However, the stability is the key to the application of foam gel, which still needs to be improved.

5. INORGANIC GEL SYSTEMS

Inorganic gel is seldom used in CO_2 storage and oil displacement. Inorganic gel is mainly based on silicate system. In recent years, efficient and flexible silicate technology has attracted great attention to oil and natural gas production.

5.1 Research status of inorganic gel gelling

The research on the application of silicate gel in oil fields began in the 1980s. Krumrine and Boyce systematically introduced the chemical properties of the aluminate silicate gel system in the early stage and described their properties, advantages, limitations, and application methods. Silicates can combine with different chemicals to improve stability. This flexibility enables it to solve the leakage problem of different fractures or high permeability reservoirs.

Castañeda-Herrera, et al. introduced Na to form an alkaline solution and neutralized the carbonic acid formed with CO_2 under high pressure and temperature to generate a silica gel plugging agent for plugging [37]. It was found that it could play a role under acidic conditions. Katoueizadeh has studied the specific process of inorganic gel gelation and again determined that pH has a greater impact on inorganic gel gelation [38]. Hatami et al. showed that the gel time was very sensitive to sol chemistry: with the increase of SiO_2 concentration, the gel time rapidly shortened; The increase in cation concentration (stronger action of divalent cations) results in a shorter gelation time; After testing, it has good chemical stability and thermal stability[39].

5.2 Advantages and disadvantages

Silicate gel system is an environmentally friendly chemical, which can be combined with different chemicals to improve its performance in all aspects. This flexibility enables it to solve the leakage problem of different fractures or high permeability reservoirs. However, inorganic gel is very sensitive to acid-base properties, and its gelling time is uncontrollable.

CONCLUSIONS

Given gas channeling and leakage problems in the process of CO_2 displacement and storage in oil and gas reservoirs, this paper summarizes four gel systems for CO_2 fluid control based on laboratory research and draws the following conclusions: polymer gel systems can adjust the formation time and rheological properties of gel through formula optimization and can improve environmental adaptability by introducing other groups. Responsive gel particles are expected to achieve in-depth profile control. Stability is a key problem in the application of foam gel. Inorganic gel system has the problem of strong pH sensitivity and uncontrollable gelling properties.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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