 https://doi.org/10.1051/e3sconf/202019401041

Study on Prevention of Gas Channelling of Acid-resistant Gel Foam in CO_2 Flooding of Low Permeability Reservoir

Zhaoxia LIU[1,*], *Ming* GAO[1], *Shanyan* ZHANG[1] and *Wanlu* LIU[1]

[1]1-State Key Laboratory of Enhanced Oil Recovery, Research Institute of Petroleum Exploration & Development (RIPED), Beijing, 100083, People's Republic of China

Abstract With the shortage of recoverable reserves in conventional oil reservoirs, the development of low-permeability oil reservoirs has received more and more attention. The oil recovery of low-permeability reservoirs can be significantly improved by CO_2 flooding, as it can effectively supply formation energy. CO_2 flooding is an effective technology for increasing oil production in low-permeability reservoirs. However, because of the heterogeneity of the reservoir and the effect of natural fractures, CO_2 gas channelling easily occurs during CO_2 flooding, seriously reducing CO_2 flooding effect. In this study, the gas channelling technology of acid-resistant gel foam was investigated. Preferred acid-resistant gel foam system formula was found as 0.1% by mass of AOS foaming agent with 0.3% to 0.4% by mass of instant HPAM polymer and 1% to 2% by mass of water-soluble phenolic resin crosslinking agent. This system still has a good foaming ability and blocking performance under at pH=2 and a salinity of 10×10^4 mg/L. After 60 days of aging under oil reservoir conditions, there is no obvious water separation, and the plugging strength retention rate reached more than 60%. The gel foam channelling system can be applied to highly heterogeneous and low permeability reservoirs with a permeability gradient higher than 14 and can increase the recovery rate by more than 20% based on the CO_2 flooding. Acid-resistant gel foam channelling technology can effectively inhibit CO_2 gas channelling and improve CO_2 flooding effect in low permeability reservoirs.

1 Introduction

In recent years, low-permeability reservoirs have been developed at an increasing rate [1]; however, problems such as difficulty in replenishing formation energy and rapid decline in production have been observed in the development of water injection. Because gas has stronger mobility than water and can easily enter the micro pore throat structure[2], gas injection has remarkably improved the development of low permeability reservoirs. Among the gases, CO_2 has been widely used in gas injection development oilfields owing to its characteristics of dissolving in crude oil, reduced oil viscosity, and easy miscibility with crude oil[3-6]. CO_2 flooding is also a major CCUS technology. However, because of the heterogeneity of low-permeability reservoirs and the existence of natural fractures, gas channelling is prone to occur during CO_2 flooding[7,8], which is severely reducing the stimulation effect of CO_2 flooding. In this study, CO_2 foam/gel foam[9] plugging control technology was investigated, and an acid-resistant plugging system was developed. In addition, the injection process parameters were optimized[10] to provide technical support for suppressing CO_2 gas channelling and improving the CO_2 flooding in low permeability reservoirs [11].

2 Experiments

2.1 Materials

Foaming agent: sodium α-olefin sulfonate (AOS), fatty acid methyl ester sulfonate (MES), sodium dodecyl sulfate (SDS), cocamidopropyl dimethylamine hydantoin (CAB-35), and fatty alcohol polyoxyethylene ether, and sodium sulfate (AES).

Polymer: Instant HPAM polymer and non-ionic HPAM polymer.

Crosslinking agent: water-soluble phenolic resin and chromium acetate crosslinking agent;

Others: Carbon dioxide (purity 99.99%), hydrochloric acid, formation water, formation oil, and low permeability long core.

2.2 Equipment

Foam evaluation device: high-speed mixer, stopwatch, high temperature aging tank, precision electronic balance, measuring cylinder, and pH meter;

Gel evaluation device: precision electronic balance, constant temperature water bath, constant control

* Corresponding author:liuzhaoxia@petrochina.com.cn

magnetic stirrer, circulating water multi-purpose vacuum pump, measuring cylinder with stopper, and pH meter;

Core displacement device: precision electronic balance, high precision plunger pump, pressure sensor, back pressure valve, intermediate pressure vessel, core holder, foam generator, thermostat, measuring cylinder, stopwatch. Fig.1 is located at the end of the paper, which shows the schematic diagram of the displacement device.

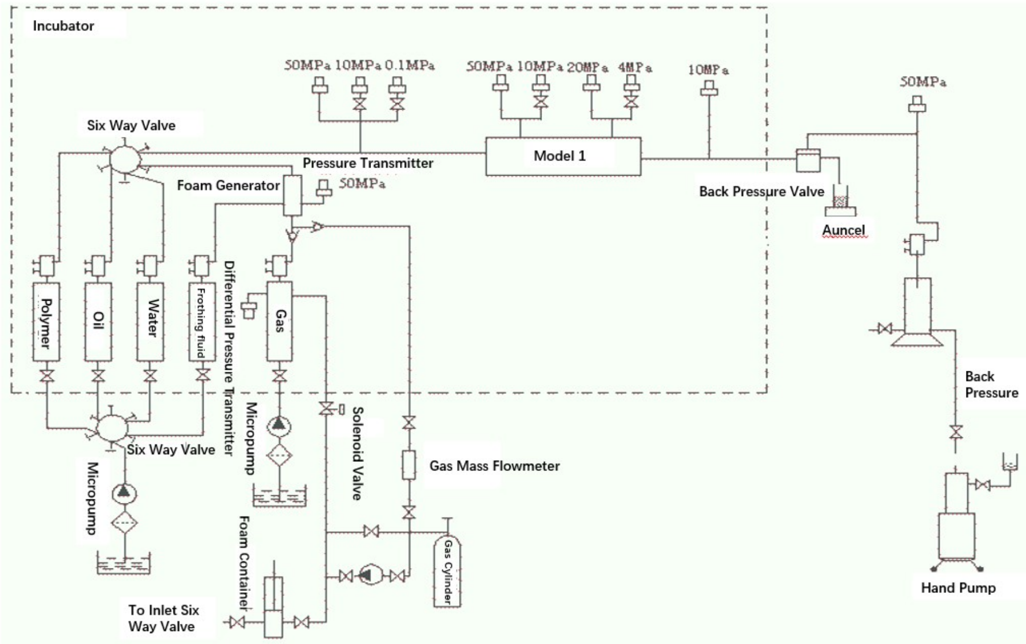

Fig.1. Schematic diagram of the core displacement device

2.3 Methods

2.3.1 Foam system optimization

Foaming agent solutions with different mass fractions were prepared following the oil and natural gas industry standard SY/T 6465-2000 "Foaming Agent Evaluation Method", stirred at high speed for 3 min at 5000 r/min, and the foaming volume and half-life were recorded. The foam comprehensive value (the volume and half-life of foam) was used as an indicator to evaluate the comprehensive performance of each foam system. Change in the salinity, pH, and aging temperature of the foam system were used to evaluate the salt resistance, acid resistance, and temperature resistance of the foam system. The foam system should be acid resistant.

2.3.2 Gel system optimization

The pH of the formation water was adjusted to 2, and different concentrations of polymer and cross-linking agent solutions were prepared for gel evaluation experiments. The Gel Strength Codes method was used to determine the freezing time, and the gel strength was determined by the vacuum breakthrough method. After the gel is frozen, it was aged at 80 °C, and the water separation and gel strength of the gel system at 30 d, 45d, and 60d aging were measured to evaluate the stability of the gel, and the acid-resistant gel system was preferred.

2.3.3 Enhanced oil recovery experiment

The conventional foam/gel foam enhanced oil recovery experiment was carried out using a heterogeneous core model to study the effect of conventional foam and gel foam on different heterogeneous reservoirs. During the experiment, CO_2 flooding was performed first, and the oil production and the pressure difference between the two ends of the model was recorded. When no oil is produced, conventional foam/gel foam was injected to perform enhanced oil recovery experiments. The foam injection method involves simultaneous injection of 1:1 gas and liquid. The experimental conditions are as follows: experimental water pH=2; water salinity is 10×10^4 mg/L; the experimental temperature is 80 °C; and the back pressure at the core outlet is 10 MPa.

3 Results & Discussion

3.1 Results of foam system optimization

CO_2 dissolves in water and is acidic; therefore, acid resistance is a necessary index for the optimization of CO_2 flooding and channelling prevention system. Among the foaming agents, CAB-35, ZYGK-3, and AOS still have good foaming performance at pH = 2 and salinity 10×10^4 mg/L. Four parts of CAB-35, ZYGK-3, and AOS foaming agent solutions were prepared, and the pH of the solution was adjusted to 7 and 2 respectively, and then the solutions were aged at 80 °C and 100 °C for 72 h after sealing. The foam performance after aging is shown in Fig 2, exhibiting good foaming ability and foam stability of AOS foaming agent after aging. Therefore, the preferred acid-resistant foam system is

 https://doi.org/10.1051/e3sconf/202019401041

AOS with a mass fraction of 0.1%. This system still has a good foaming performance at pH 2 and temperature of 100 °C, and can meet the demand of CO_2 flooding and blocking under severe conditions.

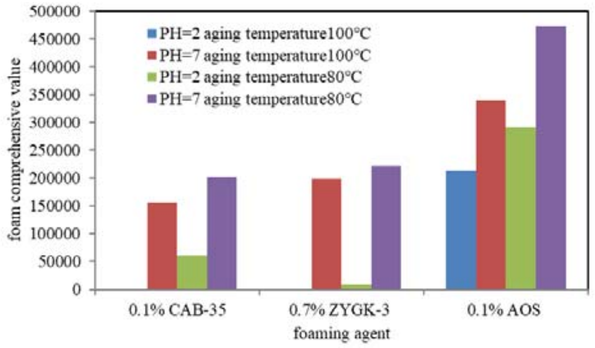

Fig. 2 Stability of foaming agents

3.2 Results of Gel system optimization

The formation water at pH 2 was used to prepare 15 mL each of instant organic chromium gel, instant phenolic resin gel, and non-ionic organic chromium gel system solution, and then aged at 80°C after gelation. The amount of water and the strength of the gel system were tested at 30d, 45d, and 60d. When going through the same aging time, phenolic resin gel has less water out than organic chromium gel, and its strength is also higher than that of organic chromium gel. The stability of instant phenolic resin gel is better than that of instant organic chromium gel and non-ionic organic chromium gel. There is no obvious water separation after 60 days' aging under oil reservoir conditions, and the strength retention rate reaches more than 60%. Therefore, an instant phenolic resin gel was preferred as the acid-resistant gel system, and the system composition is: 0.3% to 0.4% mass fraction of instant HPAM polymer and 1% to2% mass fraction of water-soluble phenolic resin cross-linking agent.

3.3 CO_2 foam plugging improves oil recovery

Aiming at different degrees of heterogeneous reservoirs, the effects of conventional foam and gel foam plugging in enhancing oil recovery were studied. The conventional foam system is 0.1 wt% AOS, and the gel foam system is 0.3 wt% instant HPAM and 1wt% water-soluble phenolic resin crosslinking agent. The core displacement model parameters are listed in Table 1.

Table. 1. Heterogeneous model parameters

Flooding model	k_h/ 10^{-3} um^2	k_l/ 10^{-3} um^2	Permeability difference
conventional foam	59.2	11.3	5.2
gel foam	109.7	7.6	14.4

3.3.1 Conventional foam improves oil recovery

The pressure difference and recovery factor curves of CO_2 gas flooding and foam flooding are shown in Fig. 3. First, gas flooding was performed at a rate of 0.15 mL/min, and then CO_2 foam was transferred after no oil is produced at the outlet. The recovery rate of CO_2 flooding is only 17%, and most of the crude oil is produced in high permeability cores. The pressure difference during gas flooding is low, and the pressure difference gradually increases after foam is injected, which indicates that CO_2 foam channelling system can effectively increase the seepage resistance in the gas channelling channel, control the flowing fluid channelling in the dominant channels, and it is suitable for plugging high permeability channels and increasing production in heterogeneous low permeability reservoir with permeability difference less than 5. In the physical simulation tests based on gas flooding, CO_2 foam plugging increased oil recovery by more than 20% in Table 2.

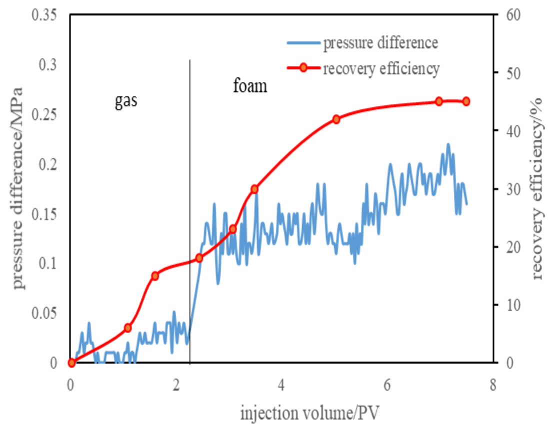

Fig. 3. Conventional foam plugging improves oil recovery performance

Table 2. Foam plugging improves oil recovery effect

Oil Recovery /%	Conventional foam	Oil recovery /%	Gel foam
Gas flooding	17	Gas flooding	8.2
Foam flooding	28	Gel foam+subsequent gas injection	42.8
Total recovery	45	Total recovery	51

3.3.2 Effect of gel foam to improve oil recovery

Aiming at strong heterogeneous reservoirs with a permeability difference of 14.5, a gel foam system with stronger sealing performance was used for investigating sealing and increasing production.

Fig.4. shows the dynamic curve of gel foam plugging and increasing production after gas flooding. First, CO_2 gas was injected at a rate of 0.15 mL/min. When no oil is produced at the core outlet, the gel foam system was injected at a rate of 0.1 mL/min and waited for 24 h to ensure that the gel foam is cross-linked to form a gel. Follow-up gas drives at a rate of 0.15 mL/min. The oil recovery of the initial gas flooding was 8.2%, and its

output was mainly from the crude oil in the gas channelling channels. When the gel foam was injected, the pressure difference increases rapidly; during the subsequent gas injection, the pressure difference increases significantly, indicating that the flow resistance of the gel foam in the gas channelling strip increases, and the viscous force increases, which can increase the amount of fluid entering the low-permeability core, and the final model recovery factor reached 51% in Table 2. Therefore, the developed gel foam plugging system effectively inhibited gas channelling in strong heterogeneous reservoirs with a permeability difference greater than 14 and improved the CO_2 flooding development effect of strong heterogeneous and low permeability reservoirs.

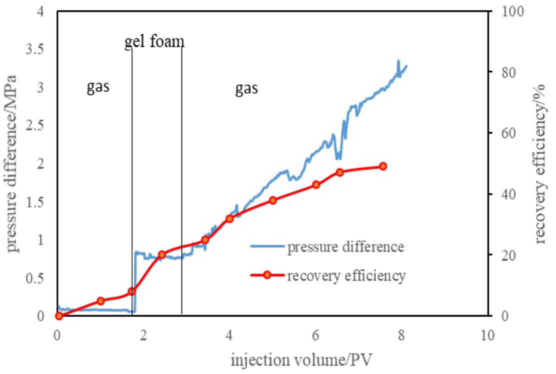

Fig. 4 Gel foam plugging improves oil recovery performance

4 Conclusions

In conclusion, the composition of the acid-resistant gel foam system is 0.1% by mass of AOS foaming agent with 0.3% to 0.4% by mass of instant HPAM polymer and 1% to 2% by mass of water-soluble phenolic resin crosslinking agent.

For weakly heterogeneous low-permeability reservoirs with a permeability difference of less than 5, on the basis of gas flooding, CO_2 foam plugging increased the recovery rate by more than 20%; for low-permeability reservoirs with a permeability difference greater than 14, gel foam adjustment and plugging can increase the recovery factor by more than 30%. The combination of CO_2 foam and gel foam control technology effectively blocked the gas channelling channels of heterogeneous low-permeability reservoirs and improved the development of low-permeability reservoirs.

Acknowledgement

This study was supported financially by the National Science and Technology Major Project, China (grant No. 2016ZX05010-005), Science and Technology Project of Exploration and Production Branch of CNPC, China (grant No. kt-2018-11-06), and National Natural Science Foundation of China.

References

1. Ping Gou，Shilun Li，Zhimin Du，et al, Journal of Southwest Petroleum University 24,5 (2002)
2. Shilun Li，Ping Gou，Lei Dai, et al, Journal of Southwest Petroleum University 8,3 (2000)
3. Chunsheng Zhu, Linsong Cheng. Drilling and Production Technology,30, 6 (2007)
4. Youzhong Lei. Technology and application of CO_2 injection for EOR in low permeability reservoir [D]. 2006, 7-9.
5. Xuefeng Yang，Ping Gou，Zhimin Du，et al, Journal of Southwest Petroleum University 26,3 (2004)
6. Peihui Han,Yanli Jiang, et al, Oilfield Chemistry, 6, (1989)
7. Xiangbin Liu．Study on CO_2 flooding channeling sealing technology in 101 block of Yushulin oilfield, Daqing [D]. Zhejiang University，2012.
8. Haidong Wang. Study on gas channeling mechanism and channeling sealing technology of CO_2 flooding [D]. Northeast Petroleum University,2017.
9. Jian Wang，Zuowei Zhang，Haibin Su，Xu Ren，Shan Qin, Fault block oil and gas field, 26, 2 (2019)
10. Xiangliang Li, Zhenquan Li, Ping Gou, et al,Petroleum Exploration and Development, 31,5 (2004)
11. Zhongyi Zhu, Yanjun Li, Inner Mongolia Petrochemical Industry 34,7 (2008)