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The application of CO_2-responsive materials on enhanced oil recovery for fractured tight oil reservoirs

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Introduction

According to the statistics, about 38% of oil and gas fields in the world and 46% in China are contributed by low-permeability reservoirs. The effective development of low permeability oil and gas fields has important strategic significance to ensure the sustainable development and exploitation of oil and gas resources in China. Due to lack of natural energy in the formation and the difficulty of water injection, the oil recovery rate and factor of these reservoirs are fairly low (WANG, et al. 2007; LI, 2020).

CO_2 flooding is often used as a EOR technology to improve oil recovery in low permeability reservoirs due to its good solubility and strong extraction ability. It is mainly used to facilitate oil displacement by reducing the viscosity of crude oil, improving the mobility ratio, expanding the volume of crude oil, and reducing the interfacial tension (ZHAO, et al. 2017). However, due to the strong heterogeneity and the existence of natural and induced fractures, as well as the influence of injection-production well parameters and fluid properties, CO_2 is prone to channeling along the high seepage zone (LI, 2018; WANG, 2019). Avoiding gas channeling during the process of gas flooding has become a major issue. It is vital to increase the sweep volume and improve the performance of CO_2 flooding to reduce the heterogeneity of reservoir and plug the breakthrough channels such as fractures, throats and pores (LIU, et al. 2022).

Water-alternate-gas (WAG) injection, gas thickening, foam plugging and polymer gel plugging are common methods to address gas channeling (PENG, 2013; YUN, 2013; WEN, 2019; ZHAO, et al. 2020). However, these measures are generally one-time plugging, which limits the effectiveness on gas channeling. In this work, a variety of CO_2 responsive plugging systems are summarized and analyzed, including CO_2 responsive foams, surfactant solutions and gels. The main mechanism of these systems is that in saturated CO_2 solution, amine-containing compounds spontaneously or combine with surfactant molecules to form worm-like micelles (WLMs) after deprotonation, so as to improve the viscosity of the solution and achieve precise and efficient blocking of gas channeling.

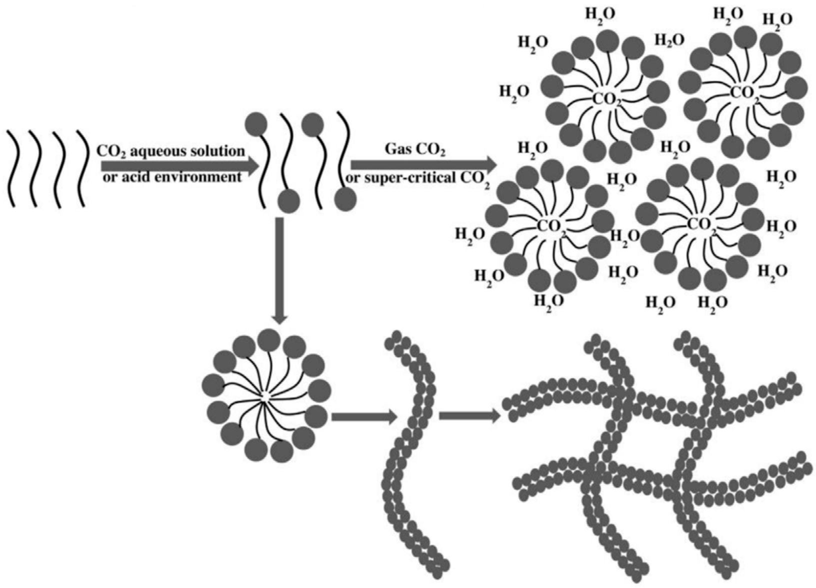

FIGURE 1
Schematic diagram of structure change of surfactant—amine system stimulated by CO_2 (LI, et al., 2015).

Types of plugging agent

CO_2-responsive foam

A formula of CO_2 responsive foam system was proposed previously by (LV, et at. 2021). The system had obvious shear-thinning characteristics and was more viscoelastic than the conventional foam system. The FCI value of the foam system could be more than 11 times than that of the conventional foam system, which could effectively inhibit gas channeling in strongly heterogeneous reservoir, and improve the CO_2 flooding development efficiency. Li et al. screened the surfactant with the best performance from five surfactants (ODPTA, AC-1810, AC-1815, SDS, OTAC) and constructed a CO_2 sensitive and self-enhanced foam system for mobility control (LI, et al. 2017). ODPTA had a carbon chain consisting of an amine group and 18 carbon atoms, which could not be ionized in water. However, in the acidic environment caused by CO_2, the amine group was protonated and ion pairs ($C_{18}H_{37}$-NH-$(CH_2)_3$-NH_2^+-$(CH_2)_3$-NH_3^+ and $C_{18}H_{37}$-NH-$(CH_2)_3$-NH-$(CH_2)_3$-NH_2-CO_2^-) are formed. The results showed that the CO_2 foam prepared by ODPTA is sensitive to CO_2 and had good plugging and mobility control performance at low concentration. Even under the harsh conditions of 7.8 MPa and 160°C, the resistance factor could still reach 274.

CO_2-responsive surfactant

Some studies showed that the use of CO_2 as an external stimulus to transform surfactant micelles was currently a simple and environmentally friendly way to prepare micelles. (SU, et al. 2013; ZHENG, et al. 2015; ZHANG, et al. 2016). Su et al. prepared an anionic worm-like micellar system with CO_2 response using sodium octadecyl sulfate ($C_{18}H_{37}SO_4Na$) and N, n-dimethylethanolamine (DMAE) at 60°C. DMAE was positively charged by protonation under CO_2 stimulation and then self-assembles with the anionic surfactant $C_{18}H_{37}SO_4Na$ under electrostatic attraction to form worm-like micelles. When N_2 was injected, the high viscosity system returned to the initial viscosity state. And this process could be repeated more than three times, and the maximum viscosity formed without a big deviation (SU, et al. 2013). Shen et al. screened ten compounds containing tertiary amine groups, and finally determined N, N-Dimethyl Erucamide tertiary amine (DMETA) as the research object. The results showed that the DMETA solution forms WLMs in saturated CO_2 solution, and the viscoelastic fluid could effectively reduce gas flow during CO_2 gas flooding in low-permeability fractured cores, and had a strong ability to withstand high temperature. WLMs had the ability of self-repair and had high residual resistance even after gas channeling (SHEN, et al. 2021).

CO_2-responsive gel

The mechanism of gel-blocking gas channeling was discussed in detail, and the future development direction of CO_2 trapping and interpenetrating gel system was prospected. CO_2 responsive intelligent gel can solve the problem of poor acid resistance of HPAM. The cross-linking formed a three-dimensional network structure after CO_2 treatment, with increased viscosity and volume, and remained stable for a long time under acidic CO_2 conditions (LIU, et al. 2022). A CO_2 responsive gel system mainly using small molecule amine (DMTA) and a modified long chain alkyl anionic surfactant (NADS) was prepared (DAI, et al. 2020). The experimental results showed that the DMTA-NADS system exhibited viscoelastic properties and shear thinning properties at high shear rates. The environment scanning electron microscope (ESEM) visually showed that the connection mode of its internal structure changed from lamellar to three-dimensional network structure. It was confirmed by NMR that amine molecules can bridge two anionic surfactant molecules by non-covalent electrostatic attraction after protonation. The core physical simulation experiment proved that the system could effectively block the CO_2 channeling channel, and the blocking efficiency was more than 90%, which increased the sweep volume of the subsequent CO_2 gas flooding and improved the recovery efficiency. It provided effective guidance for solving the practical problem of gas channeling and plugging in low permeability CO_2 gas flooding development reservoir.

Comparative analysis of different materials

The mainly mechanism of CO_2 responsive materials involved in this paper is shown in Figure 1.

It is shown that CRMs are effective measures to prevent gas channeling during gas flooding. When the CRMs encounters CO_2, its structure changes and the viscosity of the solution increases, which can be observed in both bulk and porous media. The three CRMs mentioned in this paper have essentially the same mechanism, but different plugging systems can be obtained by changing the type and concentration of surfactants, amines, and volume and rate of CO_2 injection according to different purposes of using.

Compared with other plugging agents, CRMs has a better application prospect in tight fractured reservoirs. Before CRMs gelling, the solution viscosity is low (1–2 mPa s), resulting in easy injecting. It can quickly form high viscosity gel after CO_2 injection and has strong blocking ability. Using suitable surfactants and amines, CRMs can maintain high stability under high temperature and high salt conditions.

Conclusion

1) The mechanism of CO_2 responsive plugging system is that the molecular structure in aqueous solution changes upon CO_2 stimulation, forming worm-like micelles. The macroscopic behavior is that the viscosity of the system changes, which is reversible and controllable.
2) By using different materials to interact with amine compounds, CRMs are low viscosity solutions before injection and can be formed as CO_2 responsive blocking systems after reaction with CO_2 in porous media such as CO_2 responsive foam, CO_2 responsive surfactant solution and CO_2 responsive gel. With good injection ability, CRMs can effectively block the gas channeling, force the gas to turn to the unswept zone, and improve the degree of reservoir production. At present, it is necessary to develop a low cost and high tolerance CO_2 responsive plugging system for the development of fractured tight oil reservoirs, so as to improve the production capacity and benefit of oil fields. (LIU AND LIU, 2022), (LV et al., 2021).

Author contributions

ZZ: investigation and research, writing manuscript draft; YS: resources and conceptualization; QG: modify analysis; CW: typesetting and supervision.

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Conflict of interest

Author YS was employed by the company PetroChina Ji Dong Oilfield Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Dai, M. L., Wei, F. L., Lu, Y. J., Xiong, C. M., Shao, L. M., and Song, Y. Z. (2020). A new type of CO2 responsive gel based channeling blocking system. *OIL Drill. Prod. Technol.* 45 (6), 772–778.

Li, D. X., Ren, B., Zhang, L., Ezekiel, J., Ren, S. R., and Feng, Y. J. (2015). CO2-sensitive foams for mobility control and channeling blocking in enhanced WAG process. *Chem. Eng. Res. Des.* 102, 234–243. doi:10.1016/j.cherd.2015.06.026

Li, D. X., Ren, S. R., Zhang, P. F., Zhang, L., Feng, Y. J., and Jing, Y. B. (2017). CO2 -sensitive and self-enhanced foams for mobility control during CO 2 injection for improved oil recovery and geo-storage. *Chem. Eng. Res. Des.* 120, 113–120. doi:10.1016/j.cherd.2017.02.010

Li, C. L. (2018). Gas channeling influencing factors and patterns of CO, -flooding in UItra-low permeability oil reservoir. *Special Oil Gas Reservoirs* 25 (3), 82–86. (In Chinese).

Li, Y., Xiao, K., Huang, C., Wang, J., Gao, M., and Hu, A., (2020). Enhanced potassium-ion storage of the 3D carbon superstructure by manipulating the nitrogen-doped species and morphology. *Nanomicro. Lett.* 27 (1), 1–10. (In Chinese). doi:10.1007/s40820-020-00525-y

Liu, Y. J., and Liu, Q. (2022). A review of channeling blocking gel systems for CO2 flooding. *Petroleum Geol. Recovery Effic.* 29 (3), 1–13.

Liu, F., Yue, P., Wang, Q., Yu, G., Zhou, J., and Wang, X., (2022). Experimental study of oil displacement and gas channeling during CO2 flooding in ultra—low permeability oil reservoir. *Energies* 15 (14), 5119. doi:10.3390/en15145119

Lv, W., Liu, X. C., Bai, H. L., and Peng, M. L. (2021). Laboratory test study of CO2 responsive enhanced foam system. *Pet. Drill. Tech.* 49 (5), 88–93. (In Chinese).

Peng, S. S. (2013). Gas channeling rules of CO2 flooding in extra-low permeability reservoirs in zhenglizhuang oilfield. *J. Oil Gas Technol. (J. JPI)* 35 (3), 147–150. (In Chinese).

Shen, H., Yang, Z., Li, X., Peng, Y., Lin, M., Zhang, J., et al. (2021). CO2-responsive agent for restraining gas channeling during CO2 flooding in low permeability reservoirs. *Fuel* 292, 120306. doi:10.1016/j.fuel.2021.120306

Su, X., Cunningham, M. F., and Jessop, P. G. (2013). Switchable viscosity triggered by CO2 using smart worm-like micelles. *Chem. Commun.* 49 (26), 2655–2657. doi:10.1039/c3cc37816k

Wang, G. F., Liao, R. F., Li, J. L., Yuan, X. C., Zhan, C. G., Jiang, Y. J., et al. (2007). The development situation and future of low permeability oil reservoirs of SINOPEC. *PEIROLEUM GEOIOGY RECOVERY EFFC ENCY* 14 (3), 84–89. (In Chinese).

Wang, Y. X. (2019). *Mechanism research of CO2 enhanced oil recovery for tight sand oil reservoir ——take yanchang formation 4+5 reservoir in A oil area of northern shaanxi as an example*. Kirkland,USA: Northwest University. (In Chinese).

Wen, F. G. (2019). *CO2 flooding experiment research of low permeability oil reservoir in the Ordos Basin -A case study of the Chang6 of M area of A oilfield*. Kirkland,USA: Northwest University. (In Chinese).

Yun, B. B. (2013). Field test of carbon dioxide gas channeling foam plugging. *Appl. Mech. Mater.* 2369, 316–317.

Zhang, Y., Wang, C., Liu, X., Fang, Y., and Feng, Y. (2016). CO2-Responsive microemulsion: Reversible switching from an apparent single phase to near-complete phase separation. *Green Chem.* 18 (2), 392–396. doi:10.1039/c5gc01411e

Zhao, X. S., Shi, L. H., Wang, W. B., Bai, Y., and Tian, F. (2017). CO2 channeling sealing in UItra-low-permeability reservoirs. *J. Southwest Petroleum Univ. Technol. Ed.* 39 (6), 131–139. (In Chinese).

Zhao, F., Wang, P., Huang, S., Hao, H., Zhang, M., and Lu, G. (2020). Performance and applicable limits of multi-stage gas channeling control system for CO2 flooding in ultra-low permeability reservoirs. *J. Petroleum Sci. Eng.* 192 (C), 107336. doi:10.1016/j.petrol.2020.107336

Zheng, Z. B., Liu, C. Y., and Qiao, W. H. (2015). pH-Responsive and CO2-responsive vesicles can be formed by N-decylimidazole. *Eur. J. Lipid Sci. Technol.* 117 (10), 1673–1678. doi:10.1002/ejlt.201400429