Advances in Geo-Energy Research

Vol. 15, No. 3, p. 181-184, 2025

Perspective

# Theory and technology of enhanced oil recovery by gas and foam injection in complex reservoirs

Hailong Chen[1], Bing Wei[1], Xiang Zhou[1]*, Jingyi Zhu[2], Zhengxiao Xu[3]*, Yousheng Fan[1]

[1]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, P. R. China
[2]College of Chemistry and Chemical Engineering, Southwest Petroleum University, Chengdu 610500, P. R. China
[3]School of Petroleum and Natural Gas Engineering, Changzhou University, Changzhou 213164, P. R. China

**Keywords:**
Enhanced oil recovery
vuggy reservoirs
gas injection
foam injection

**Cited as:**
Chen, H., Wei, B., Zhou, X., Zhu, J., Xu, Z., Fan, Y. Theory and technology of enhanced oil recovery by gas and foam injection in complex reservoirs. Advances in Geo-Energy Research, 2025, 15(3): 181-184.
https://doi.org/10.46690/ager.2025.03.01

**Abstract:**
To meet the growing energy demand and ensure national energy security, improving the recovery rate of developed oil fields and tapping into their remaining oil potential have become important ways to stabilize crude oil production. Given the constraints posed by the intricate nature of reservoir formation conditions and the properties of crude oil, including high viscosity, significant heterogeneity, and low permeability, certain techniques find it challenging to be effectively utilized. In view of this, this article introduces enhance heavy oil recovery by *in-situ* generated foamy oil, foam flooding in deep fractured vuggy reservoirs, and a new $CO_2$ responsive fracturing foam fluid, respectively. These results can provide constructive conclusions and suggestions for the study of theories and methods of enhanced oil recovery by gas and foam injection in complex reservoirs.

## 1. Introduction

Injecting gas to improve crude oil recovery is a technical means in oilfield development. Its significant advantages include: (i) Excellent injection performance of the gas, which facilitates the construction of an efficient displacement pressure system, (ii) It can produce significant mixing effects or reduce oil-water interfacial tension after gas injection, while achieving volume expansion and reducing crude oil viscosity, effectively increasing the coverage range and improving oil displacement efficiency, (iii) Gas injection technology has diverse gas source options and flexible injection strategies, making it widely applicable to different types of oil fields (Yuan et al., 2020; Chen et al., 2024). Foam fluid has the characteristics of adjustable density, low filtration rate, little damage, and high sand carrying capacity. At the same time, foam fluid has the characteristics of selective plugging in the formation. In the past 20 years, a series of foam stimulation technologies have been gradually formed, including foam fracturing, foam acidizing, foam profile control, foam oil displacement, etc., which have been successfully applied and promoted on the site, and have achieved good application results under complex oil and gas production conditions.

In addition, if the gas component in gas injection/foam is $CO_2$, it can meet the requirements of $CO_2$ utilization and storage while enhanced oil recovery of complex oil reservoirs, namely carbon dioxide capture, EOR-utilization and storage (CCUS-EOR). This technology is not only an important measure to achieve "carbon peak and carbon neutrality" in China, but also a strategic replacement technology to significantly improve the recovery rate of low permeability oil fields, heavy oil reservoirs and other complex oil fields (Chen et al., 2020a; Wang et al., 2023; Wu et al., 2023). Given these considerations, this article focuses mainly on these three aspects, namely, enhance heavy oil recovery by *in-situ* generated foamy

Yandy Scientific Press

*Corresponding author.
*E-mail address*: chenhailong0515@163.com (H. Chen); bwei@swpu.edu.cn (B. Wei); shawnzhou326@126.com (X. Zhou); jingyizhu@swpu.edu.cn (J. Zhu); xzx@cczu.edu.cn (Z. Xu); fyswpu1207@163.com (Y. Fan).

Received November 28, 2024; revised December 14, 2024; accepted December 25, 2024; available online December 27, 2024.

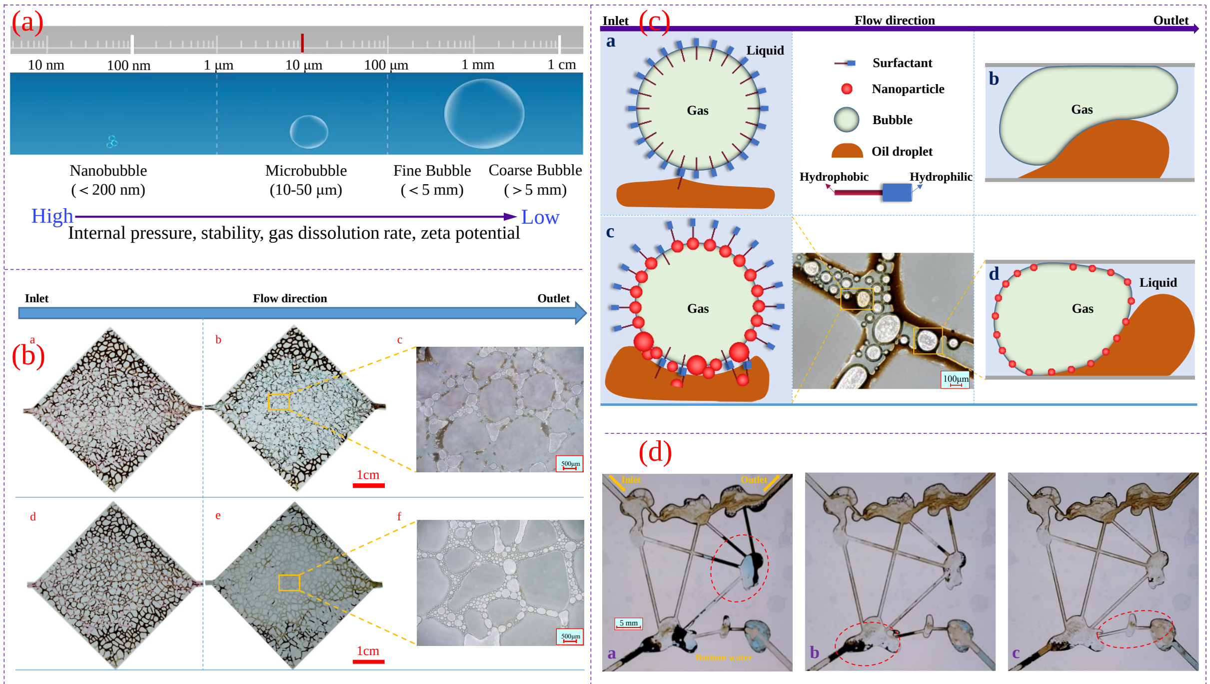


**Fig. 1**. (a) The relationship between foam stability and foam size, (b) comparison of foam flooding effects, (c) schematic diagram of foam flooding mechanism and (d) comparison of oil displacement effects in fractured vuggy model (Zhou et al., 2021; Xu et al., 2020, 2022).

oil, foam flooding in deep fractured vuggy reservoirs, and a new $CO_2$ responsive fracturing foam fluid, and proposes some related questions, challenges, conclusions, and suggestions.

## 2. Enhance heavy oil recovery by *in-situ* generated foamy oil

The primary production process is one of the main recovery approaches for heavy oil reservoirs, and foamy oil flow serves as the primary mechanism driving the primary production process. The studies of foamy oil flow have been widely considered in heavy oil recovery in both depletion production process and the gas injection process applied in the heavy oil reservoirs. In the primary depletion process, the gas phase is the solution gas in the reservoir. But in the gas injection process, the mainly studied gas are $CO_2$, $CH_4$, $C_2H_6$, $C_3H_8$, $N_2$ etc. (Chen et al., 2020b). Due to its relatively higher oil recovery factor compared to the primary production process, foamy oil flow is highly regarded in gas injection processes, particularly in $CO_2$ injection processes. With the foamy oil flow in the gas injection process, the oil recovery factor in the lab scale can be reached up to 38.02%, which is much higher than the primary production process (Zhou et al., 2019).

In the $CO_2$ injection process, the full-live of foamy oil flow in the reservoir can be divided into bubble nucleation, bubble growth and bubble coalescence (Maini, 2001). Once $CO_2$ was injected into the heavy oil reservoir, $CO_2$ was dissolved into heavy oil, and in the production process the foamy oil was generated, the gas phases changed with pressure decline, thus the total volume of the foamy oil changing with the pressure, leading to oil production with the volume of foamy oil changing. Meanwhile, the foamy oil stability is related to pressure depletion rates, with the pressure depletion rate increases, the foamy oil stability and the relative volume of foamy oil are enhanced, therefore, higher depletion rate can gain better foamy oil stability and oil production performance (Zhou et al., 2022). Equation 1 shows Zhou‘s equation, which developed from the long-core $CO_2$ huff-n-puff experiments, and the soaking time, pressure depletion rate and cycle number were optimized as 1 kPa/min, 5 hours and cycle 3, respectively. The formulated equation can be utilized to forecast oil and gas production in the foamy oil flow using $CO_2$ injection process for both single cycle and the whole production process:

$$N_p = a\left(\frac{\sqrt{\lg G_p}}{N_p}\right)^b \tag{1}$$

where $N_p$ represents the cumulative oil production; $a$ and $b$ are coefficients that are dependent on operational parameters and reservoir properties; $G_p$ denotes the cumulative gas production.

## 3. Foam flooding in deep fractured vuggy reservoirs

At present, extreme conditions of high salinity and high temperature seriously restrict the development of foam flooding technology in deep fractured vuggy carbonate reservoirs. Preliminary studies have revealed that by considering the structure-activity relationship of surfactant molecules and introducing temperature and salt resistant functional groups, the

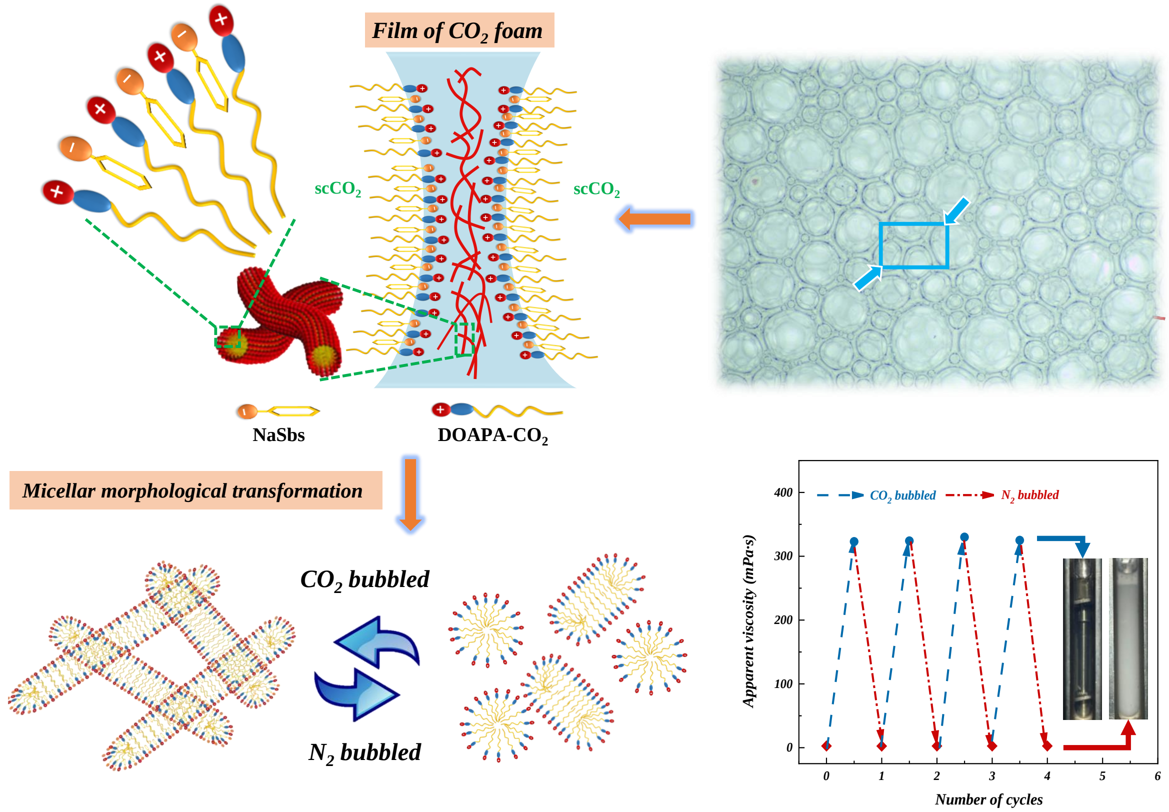


**Fig. 2**. $CO_2$-responsive VES-$CO_2$ foam fracturing fluid stabilization mechanism and performance.

tolerance of foam system to temperature and salinity can be improved to 150 °C and $2 \times 10$ mg·L$^{1}$, respectively. In addition, the stability of foam can be controlled from the perspective of foam size by adjusting the preparation process, as illustrated in Fig. 1(a).

Theoretically, based on the Kelvin foam structure and liquid holdup model, foam drainage equations can be established, and various foam flow experiments can be conducted within typical fractured vuggy units using multidimensional, multiscale models. By employing models with variable pore sizes, parallel fractures, and complex fracture networks, the impact of fracture distribution on foam flow can be assessed. Additionally, the transparency of fractures facilitates flow visualization and provides clear characterization and statistical data for foam morphology, stability, and other properties. Within a foam quality range of 50% to 90%, increasing foam quality results in higher flow resistance, while flow resistance decreases when foam quality exceeds 90%. When foam quality reaches approximately 90%, the pressure difference peaks. By combining machine learning techniques, deeper insights into the structural evolution of foam are gained, laying a foundation for studying flow dynamics in fractures and cavities.

To examine the oil displacement behaviors of foam fluids, microfluidic platforms have been used for micro-visualization experiments. Comparative analysis with standard foam shows that the addition of nanoparticles significantly enhances the sweep efficiency and oil recovery of foam, as illustrated in Fig. 1(b). Nanoparticle-stabilized foam reduces the volume of dead-end dead oil by more than 33%. Further understanding of foam-assisted oil recovery mechanisms, as depicted in Fig. 1(c), led to preliminary oil displacement experiments using various techniques within a micro-scale fractured-vuggy model. These experiments confirmed the remarkable effectiveness of foam flooding in such systems, with recovery factors increasing by up to 50%, as shown in Fig. 1(d).

## 4. A new $CO_2$ responsive fracturing foam fluid

Viscoelastic surfactant (VES) cleaning fracturing fluid presents a viable solution to the issue of reservoir damage associated with traditional fracturing fluids. However, its implementation is hindered by its relatively high cost. On the other hand, $CO_2$ foam fracturing fluid boasts advantages such as easy backflow, minimal filtration, and robust proppant carrying capacity, making it particularly suited for fracturing operations in water-sensitive and low-pressure heterogeneous reservoirs. The integration of these two technologies results in a novel type of fracturing fluid known as VES-$CO_2$ foam fracturing fluid. It combines the beneficial attributes of the two fracturing fluids, and can reduce VES cost by 60%-90% and water consumption by more than 70% because of the 60%-90% foam quality of foam fracturing fluid (Wanniarachchi et al., 2017). To some extent, this method can solve problems of massive freshwater consumption, reservoir damage, high costs, and water sensitivity.

High performance VES-$CO_2$ foam fracturing fluid system can be prepared by using $CO_2$ responsive surfactant as the basic component, and current research shows that DOAPA converts to a cationic surfactant, DOAPA-$CO_2$, under the stimulation of $CO_2$. In the presence of Nasbs, these surfactants form worm-like micelles, which increase the viscosity of the foaming solution from 12 mPa·s to 2,869.69 mPa·s. Moreover, with the help of synthetic resonance technology, the circulation mechanism of $CO_2$ responsive foam fracturing fluid is clarified by analyzing the structural changes of $CO_2$ responsive surfactant before and after stimulation. This analysis confirms that the system will not change the underlying fluid environment after multiple cycles (Tang et al., 2018). Under high-pressure conditions, the settling rate of the proppant stabilizes below 2.4 cm/min, meeting engineering standards. By adjusting the $CO_2$ level, the fracturing fluid can undergo gel breakdown, allowing the foam viscosity to switch between low and high states (Fig. 2). Furthermore, the damage rate of the new fracturing fluid is as low as 8.08%, indicating its compatibility with both the reservoir and fractures (Zheng et al., 2024).

## 5. Challenges and perspectives

Because of the effect of the porous media, the foamy oil characters are much more complex in the *in-situ* reservoirs. The visible study of foamy oil in the porous media is urgent to be implemented, so that the character of foamy oil in the reservoir can be clearly understood. The stability of the foamy oil indicates the dura whole life of the foamy oil, how to enhance the stability of the foamy oil using special materials such as nano material, chemicals etc. is another perspective.

Foam flooding technology has been successfully applied in shallow sandstone reservoirs, but its development and application in fractured vuggy reservoirs remain limited to pilot tests. Moreover, Breakthroughs are needed in both foam formulation and foaming processes to enhance stability under high-pressure, high-temperature conditions.

In complex field operations, the returned fluids may contain large amounts of sand, formation water, and crude oil. Ensuring that the VES-$CO_2$ foam fracturing fluid maintains excellent recyclability in these complex environments will be a key focus for future research.

## Acknowledgements

The authors gratefully acknowledge financial support from the Natural Science Foundation of Sichuan Province (No. 2024NSFSC0977), Project funded by China Postdoctoral Science Foundation (No. 2023M742903).

## Conflict of interest

The authors declare no competing interest.



## References

Chen, H., Ji, B., Wei, B., et al. Experimental simulation of enhanced oil recovery on shale rocks using gas injection from material to characterization: Challenges and solutions. Fuel, 2024, 356: 129588.

Chen, H., Li, H., Li, Z., et al. Effects of matrix permeability and fracture on production characteristics and residual oil distribution during flue gas flooding in low permeability/tight reservoirs. Journal of Petroleum Science and Engineering, 2020a, 195: 107813.

Chen, T., Leung, J. Y., Bryan, J. L., et al. Analysis of non-equilibrium foamy oil flow in cyclic solvent injection processes. Journal of Petroleum Science and Engineering, 2020b, 195: 107857.

Maini, B. B. Foamy-oil flow. Journal of Petroleum Technology, 2001, 53: 54-64.

Tang, Q., Huang, Z., Zheng, C., et al. Switchable surfactant-based $CO_2$-in-water foam stabilized by wormlike micelle. Industrial & Engineering Chemistry Research, 2018, 57(40): 13291-13299.

Wang, H., Cai, J., Su, Y., et al. Pore-scale study on shale oil-$CO_2$-water miscibility, competitive adsorption, and multiphase flow behaviors. Langmuir, 2023, 39: 12226-12234.

Wanniarachchi, W. A. M., Ranjith, P. G., Perera, M. S. A. Shale gas fracturing using foam-based fracturing fluid: A review. Environmental Earth Sciences, 2017, 76: 91.

Wu, R., Wei, B., Li, S., et al. Enhanced oil recovery in complex reservoirs: Challenges and methods. Advances in Geo-Energy Research, 2023, 10(3): 208-212.

Xu, Z., Li, Z., Cui, S., et al. Flow characteristics and EOR mechanism of foam flooding in fractured vuggy reservoirs. Journal of Petroleum Science and Engineering, 2022, 211: 110170.

Xu, Z., Li, B., Zhao, H., et al. Investigation of the effect of nanoparticle-stabilized foam on EOR: Nitrogen foam and methane foam. ACS Omega, 2020, 5(30): 19092-19103.

Yuan, S., Wang, Q., Li, J., et al Technology progress and prospects of enhanced oil recovery by gas injection. Acta Petrolei Sinica, 2020, 41(12): 1623-1632.

Zheng, N., Zhu, J., Yang, Z., et al. Research on the viscoelastic $scCO_2$ foam systems synergistically stabilized by nonionic/zwitterionic mixed surfactants. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2024, 697: 134462.

Zhou, L., Wang, S., Zhang, L., et al. Generation and stability of bulk nanobubbles: A review and perspective. Current Opinion in Colloid & Interface Science, 2021, 53: 101439.

Zhou, X., Yuan, Q., Rui, Z., et al. Feasibility study of $CO_2$ huff 'n' puff process to enhance heavy oil recovery via long core experiments. Applied Energy, 2019, 236: 526-39.

Zhou, X., Li, X., Shen, D., et al. $CO_2$ huff-n-puff process to enhance heavy oil recovery and $CO_2$ storage: An integration study. Energy, 2022, 239: 122003.