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Perspective

Enhanced oil recovery in complex reservoirs: Challenges and methods

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Abstract:
Enhanced oil recovery draws increasingly interests from the research and development phases to oilfield implementation worldwide. Due to the complexity of the developed reservoirs and requirement of carbon footprint reduction, new innovations are urgently needed to increase enhanced oil recovery efficiency and/or reduce emissions simultaneously. This paper presents the strategies to improve the enhanced oil recovery performance of carbon dioxide flooding, polymer flooding and imbibition in complex reservoirs. Field trials conducted at Mahu reservoirs demonstrated the potential of nanoemulsion imbibition in stimulating tight oil recovery. These results can provide constructive envision for the development and application of enhanced oil recovery technologies for challenging systems.

1. Introduction

Enhanced oil recovery (EOR) refers to produce an additional oil recovery beyond primary and secondary oil recovery through the injection of fluids and energy that are not normally present in reservoirs. As the discovery rate of new hydrocarbon resources decreases, the need for more-efficient EOR processes is necessary. The injectants must accomplish at least one of the following objectives:

i) Supplement the natural energy of the reservoir;

ii) Stimulate the interactions with rock/oil system to create favorable conditions for recovering residual oil (Green and Whillhite, 1998). For example: correction of mobility ratio between the displacing fluid and oil; lowering the interfacial tension between the displacing fluid and oil; alteration of rock wettability towards water-wet condition; reduction of oil viscosity; swelling oil; miscibility.

The current EOR methods can be generally categorized into five groups: mobility-control, chemical flooding, miscible injection, thermal processes, and other EOR method, as illustrated in Fig. 1.

In China, EOR technologies have been used to increase oil recovery after waterflooding since 1970s. Due to the complexity of reservoir conditions in terms of rock lithology and petrophysical properties, physicochemical properties of crude oil, temperature, and pressure, the efficiencies of EOR processes vary dramatically across different plays. This is particularly significant with the exploration and development of hydrocarbons toward complex reservoirs such as low-permeability reservoirs. Moreover, unlike in the past, when the efficiency was defined as maximizing the recovery factor, the new interpretation of efficiency is based on optimizing the balance between recovery factor and carbon footprint reduction (Tapia et al., 2018; Jiang et al., 2020). Given these considerations, when choosing EOR methods, new innovations

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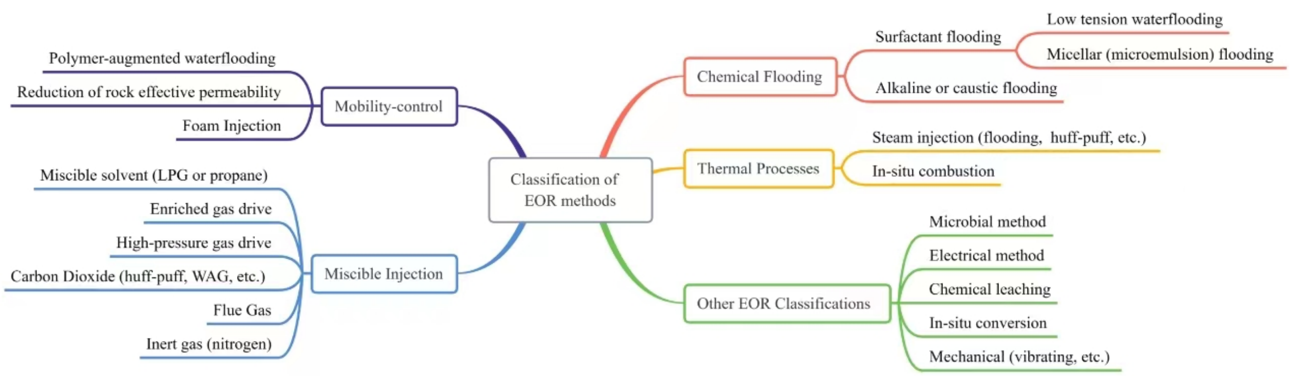

Fig. 1. Classification of EOR methods (reproduced after Romero-Zerón (2012)).

or emerging processes are highly needed to address the challenges in complex reservoirs. The primary attention of this paper is placed on the recent advances of EOR processes in carbon dioxide (CO_2) flooding, polymer flooding and field trials. Our perspectives are also presented.

2. CO_2-EOR and storage

Over the past century, global temperatures have experienced a significant rise, averaging 1.1 °C compared to the levels in 1850. China has outlined an ambitious development goal of reaching carbon peak by 2030 and achieving carbon neutrality by 2060 (Zhang and Xu, 2023). The emission trajectory aligned with China's carbon-neutral vision includes four stages: the peak period, plateau period, decline period, and neutral period. Nevertheless, the reduction of CO_2 emissions from 12 billion tons per year to zero in approximately 30 years is extremely challenging. The technology of CO_2-EOR and storage presents a viable solution, which can effectively improve oil recovery and facilitate carbon storage considering both economic benefits and environmental preservation. This technology has gained considerable attention globally. Fractured low-permeability and tight reservoirs are characterized with extremely high heterogeneity and indicated by huge permeability contrast. Therefore, it is of great importance to achieve quality and efficiency for this type of reservoirs. As reported, CO_2 flooding was able to achieve an oil recovery of 90% original oil in place under miscible conditions (Zhang et al., 2022). Miscible flooding projects in North America accounts for 93% of gas injection; however, 70%-80% of low-permeability reservoirs in China cannot achieve miscibility (Zhang et al., 2018; Wang et al., 2023b, 2023d). Hence, it becomes necessary to decrease miscible pressure and then increase oil recovery under immiscible conditions. For unconventional reservoirs that are suitable for gas injection, CO_2 is directly injected into the reservoir. Due to the low viscosity of CO_2 and gravity difference, the sweep efficiency is only 25%, and the utilization rate of subterranean space is very low. CO_2 foam can effectively decrease CO_2 mobility, and thus expand the sweep volume of CO_2 in the formation, which consequently improves the efficiency of carbon storage and the utilization of subterranean space (Li et al., 2020; Zhang et al., 2020; Wang et al., 2023c; Wen et al., 2023).

The increase of CO_2-EOR and storage efficiency using surfactants and foam is illustrated in Fig. 2. From Fig. 2(a), the mechanism of miscible pressure reduction after surfactant addition is presented. The oil and gas box was simulated at 2,000 ps before and after surfactant addition. With the process of simulation, the miscible degree of CO_2 and oil gradually increases. At the end of experiment, the oil-gas interface without surfactants remains obvious under the same pressure. Fig. 2(b) shows the variation in the three-phase saturation path of oil-gas-water during CO_2 flooding and high dryness foam flooding. High dryness aqueous foam flooding demonstrates the longest saturation path, with the highest increase in gas saturation and a significant decrease in oil saturation, indicating enhanced CO_2 storage. In Fig. 2(d), the production performance after CO_2 flooding and CO_2 oil-based foam flooding are presented. The pressure difference in CO_2 flooding is relatively low, with a maximum value of 0.04 MPa. After gas channeling, oil recovery barely increases and finally reaches a recovery of only 17.8%. CO_2 oil-based foam domenstrates superior plugging ability, which, therefore, mitigates gas channeling and expands the sweep volume. The maximum pressure difference during CO_2 oil-based foam flooding is 0.67 MPa, and the final recovery rate is 64.3%. CO_2 oil-based foam significantly increases the oil recovery and facilitates CO_2 storage.

3. Transport of self-adaptive polymer through porous media

For over half a century, oilfield chemicals have become indispensable materials for oil and gas production. However, the harsh oil and gas environments such as low-permeability, high temperature and high salinity, as well as acidic conditions during CO_2 flooding, raise new challenging issues (e.g., mechanical degradation, sharp viscosity reduction, and acid hydrolyzation) to the development of organic oilfield chemical materials such as polymers and surfactants. The traditional "passive resistance" strategy like the introduction of functional groups and an increase in molecular weight (MW) cannot fully meet the requirements. A new idea of "environmentally self-adaptive oilfield chemical materials" was proposed by Feng (2020), whose performances can be spontaneously adjusted with changes in environmental conditions.

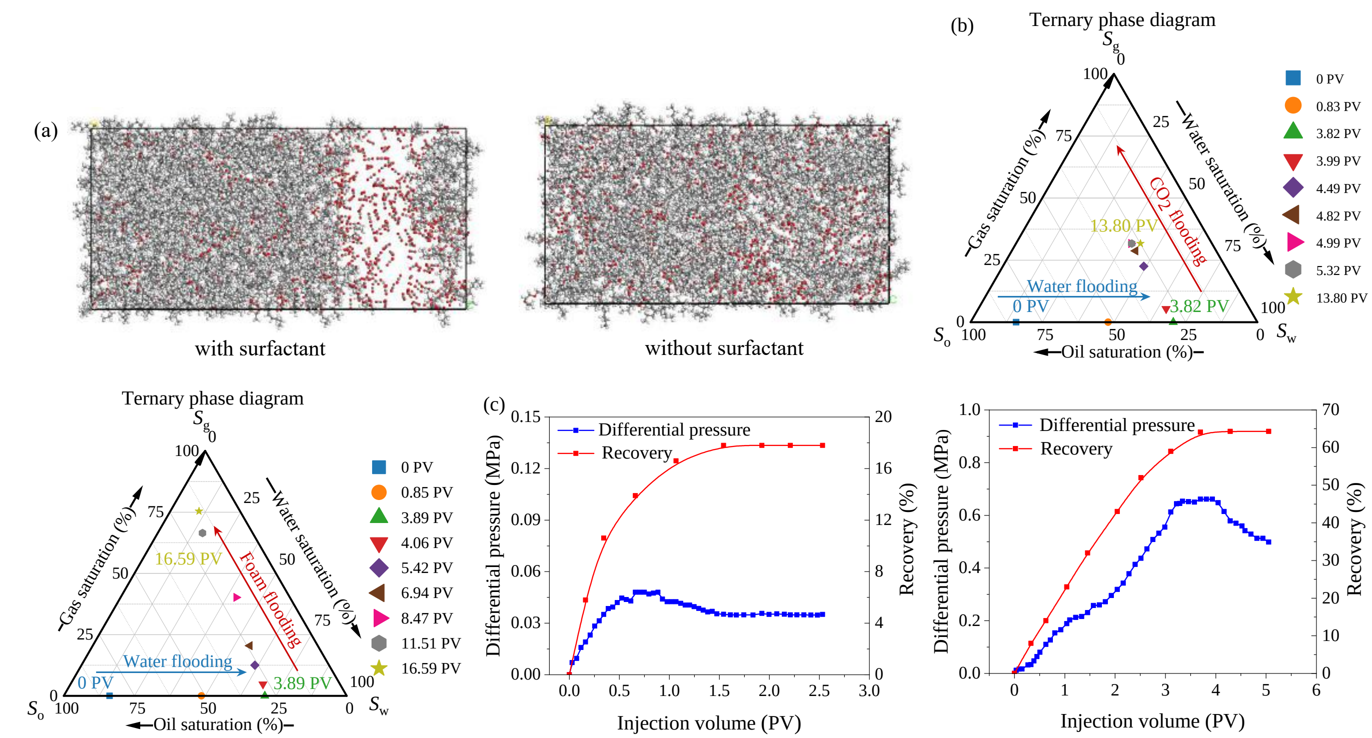

Fig. 2. Improving CO_2-EOR and storage efficiency by surfactant and foam: (a) The mechanism of miscible pressure reduction using surfactant (Wang et al., 2023d), (b) three-phase saturation path in CO_2 flooding (left) and high dryness foam flooding (right) and (c) characteristics of CO_2 flooding (left) and oil-based CO_2 foam flooding (right) in fractured cores (Li et al., 2020).

To date, a series of materials were successfully developed including permeability-adaptive polymers (Zhang et al., 2019), temperature-adaptive polymers (Wang et al., 2010, 2018; Li et al., 2021), salinity-adaptive polymers (Li et al., 2019), CO_2-adaptive polymers (Luo et al., 2021) and viscoelastic surfactants (Zhang et al., 2013a; Luo et al., 2023), and pH-adaptive viscoelastic surfactants (Chu and Feng, 2010; Zhang et al., 2013b; Feng and Chu, 2015). To prove the occurrence of self-adaptive behavior in situ, understanding the flow dynamics of their solutions in porous media is indispensable yet lacking.

Taking a low-MW (8.7 million) permeability-adaptive polymer (self-adaptive polymer (SAP) whose microscopic association structure and macroscopic viscosity can reversibly change in response to shear action (Fig. 3(a))) as an example, its solution's flow and displacement characteristics were investigated using microfluidic-based "rock-on-a-chip" devices. First, the hydrophobic-effect-driven reversible association/dis-association processes of SAP were directly observed in a two-dimensional ordered pore-throat geometry model (Fig. 3(b)) by fluorescently labeling hydrophobic aggregates under confocal microscopy (Fig. 3(c)) (Zhang et al., 2023a). Then, three-dimensional-media (Fig. 3(d)) analysis indicated that although both SAP and non-adaptive polymers (hydrolyzed polyacrylamide (HPAM)) exhibit flow thinning and then thickening regions as the flow rate increases (Fig. 3(e)), the adaptive character not only extends SAP's shear-govern region, allowing SAP to propagate piece by piece and achieve higher accessible pore volume (Fig. 3(f)), but it also enhances the elastic resistibility of polymer in the extension-dominated regime, increasing the microscopic displacement efficiency (Zhang et al., 2023b). As a result, SAP can improve oil recovery up to 18.7% in a 60 mD core, which is roughly three times higher than that of the MW-equivalent analogue, HPAM-1 (8.2 million) (Zhang et al., 2019).

In summary, the environmentally self-adaptive concept could pave the way for the molecular design of oilfield chemicals used in challenging hydrocarbon production. Moreover, the studies offer a new approach to exploring the physics of the flow and transport of weakly interacting polymer solutions or other complex fluids through complicated and realistic porous media. In fact, microfluidic-based visual technique was developed to investigate in-situ emulsification, micro-emulsification, and micellar solubilization during surfactant flooding in our group (Zhao et al., 2020, 2022a, 2022b).

4. Field trials

Mahu tight conglomerate reservoir has demonstrated significant development potential, which primarily employs the development method of horizontal well drilling coupled with fracturing (Wang et al., 2023a). However, due to the unfavorable reservoir properties and pronounced heterogeneity, the decline of production rate is rapid, resulting in a low recovery factor of less than 5% (Yu et al., 2018). In addition, as a result of insufficient reservoir energy, there is a substantial risk of well shutdowns after pumping. In this case, implementation of reservoir energy replenishing technologies is urgently required. The energy replenishing of tight oil reservoirs is primarily

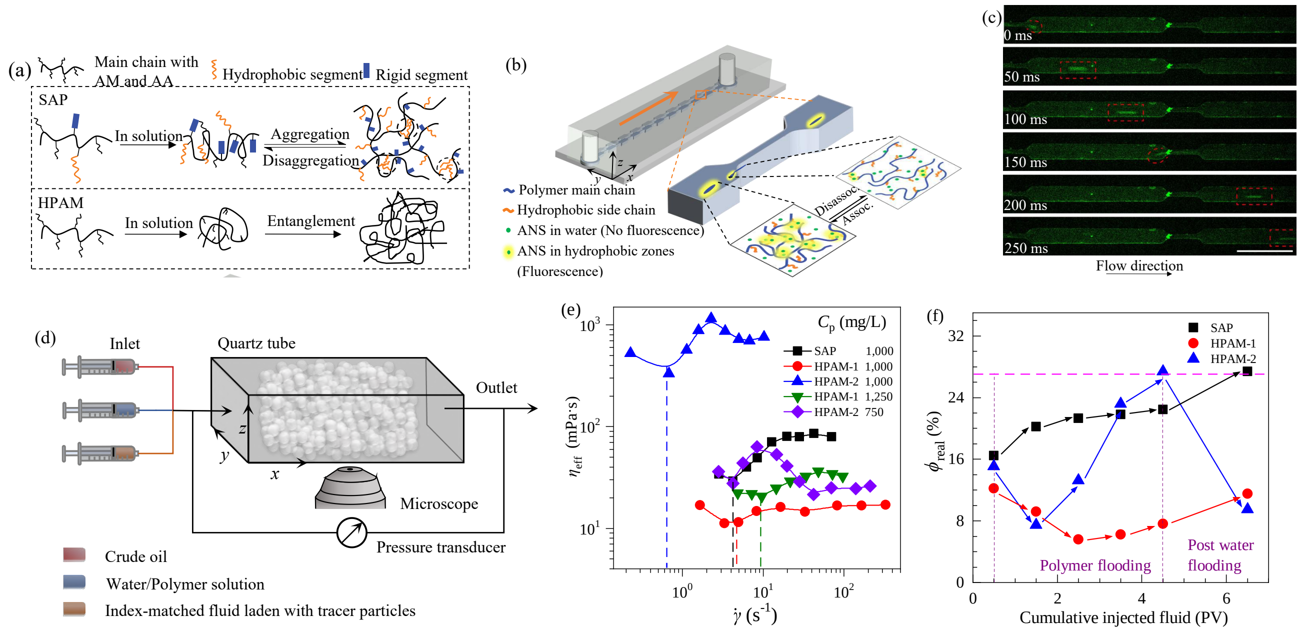

Fig. 3. Investigation of flow and displacement behaviors of SAP solution compared to HPAM-1, as well as an ultra-high-MW reference (25 million), HPAM-2: (a) Scheme of morphologies of SAP and HPAM in aqueous solution (Zhang et al., 2019), (b and c) schematic diagram and confocal images (scale bar, 200 μm) of the SAP solution with dye at different times in a sample converging-diverging section of the two-dimensional pore-throat model (Zhang et al., 2023a), (d) schematic diagram of the three-dimensional porous medium and the flow chart of displacement experiments (Zhang et al., 2023a), (e) the in-situ viscosities (η_{eff}) as a function of the average shear rate of the porous medium ($\dot{\gamma}_{pm}$) (Zhang et al., 2023b) and (f) variation of average real-time porosity (ϕ_{real}) as a function of the cumulative volume of injected fluids for SAP and HPAM solution at a same concentration (Zhang et al., 2023b).

accomplished by liquid injection (water, surfactant solution, nanoemulsion, etc.) and gas injection (CO_2, N_2, hydrocarbons, etc.). However, due to the poor reservoir conditions and influence of artificial fractures, issues such as injection failure or channeling usually lead to undesirable performance of gas injection. Thus, liquid injection holds potentials currently in terms of economic and technical viability. Rigorous characterizations were performed to assess the imbibition efficiency of nanoemulsion injection in Mahu reservoir. The results indicate that: (i) Mahu reservoir exhibits irreducible water primarily residing in nanometer-sized pores with a diameter smaller than 0.1 μm. The remaining oil within these pores accounts for 58.35% of the total remaining oil in the core; (ii) nanoemulsion imbibition increases the oil recovery by 23.3%, in which 73.6% of the recovered oil is contributed by nanoscale pores; (iii) the imbibition efficiency decreases from 19.64% in the first cycle to 2.3% in the fourth cycle.

Field trials of nanoemulsion imbibition were extensively conducted in Ma-18 and Ma-131 well blocks. In total of 146 wells are included, resulting in an incremental oil production of 124,000 tons and a cost-effectiveness ratio of 1:4.5.

The following suggestions are made to further improve the EOR performance in Mahu reservoir: (i) In-depth investigations on various types of surfactants are greatly necessary to provide a basis for screening and optimizing surfactant system. The focus should be on the evaluation of their capabilities to reduce interfacial tension and alter wettability; (ii) Mahu reservoir demonstrates diverse pore structures; therefore, a further clarification of adaptive formulations and processes for different pores should be made; (iii) to address the uneven utilization of horizontal lateral, it is essential to conduct process-oriented research to further increase the recovery factor.

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