Miscibility effect on CO2-EOR and storage in fractured low-permeability reservoirs

Introduction

Rising carbon dioxide emissions have exacerbated global climate warming, rendering carbon capture, utilization and storage (CCUS) a vital strategy for low-carbon energy development. The coupling of CO_2-enhanced oil recovery (CO_2-EOR) and geological carbon storage offers distinct advantages for developing low-permeability reservoirs, as the integrated technique delivers incremental oil production while permanently storing CO_2 in subsurface formations. CO_2-crude oil miscibility is a key factor governing oil displacement efficiency and CO_2 storage performance. However, how CO_2 trapping mechanisms dynamically evolve across immiscible, near-miscible and fully miscible flooding regimes remains poorly clarified. This work develops a fully coupled numerical model to systematically investigate oil production responses, CO_2 migration behaviors, trapping mechanism transitions, and long-term storage sustainability. The results elaborate how miscibility governs the evolution of dominant CO_2 storage pathways and reservoir petrophysical properties, offering actionable theoretical insights for designing efficient, safe CO_2-EOR and storage operations in fractured low-permeability reservoirs.

Method and/or Theory

In this study, a fully coupled thermal-hydraulic-chemical numerical model is established for fractured low-permeability reservoirs using the CMG-GEM simulator (Figure 1). The detailed modeling procedures are outlined below:

1) A 3D geological model is built by incorporating well logging data, microseismic monitoring datasets and field fracture distributions, which accurately characterizes reservoir heterogeneity and defines the stimulated reservoir volume (SRV).

2) Laboratory differential liberation and slim tube tests are performed to calibrate reservoir fluid phase behaviors and determine critical parameters, with the minimum miscibility pressure (MMP) as the core indicator.

3) The Peng–Robinson equation of state (PR-EOS) is applied to compute multiphase equilibrium states and interphase mass transfer between CO_2, oil and formation water.

4) The Carlson–Land relative permeability model is adopted to characterize gas hysteresis effects, enabling quantitative assessment of residual CO_2 trapping potential in porous media.

5) A geochemical reaction module is embedded into the numerical framework to replicate subsurface aqueous reactions and mineral dissolution-precipitation cycles. The Kozeny–Carman correlation is utilized to quantify dynamic variations in reservoir porosity and permeability.

6) Three CO_2 flooding schemes covering immiscible, near-miscible and miscible conditions are designed, encompassing four consecutive development phases: primary depletion, CO_2 flooding injection, post-injection CO_2 storage, and 200-year long-term geological stabilization.

The integrated model is capable of quantifying six distinct subsurface CO_2 storage forms and dynamically tracking the contribution rate of four primary

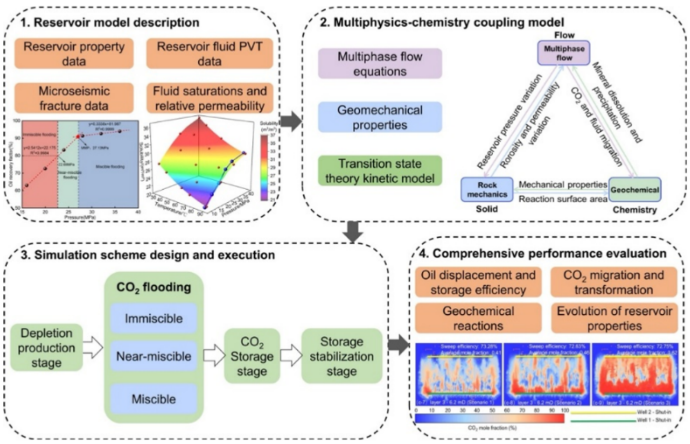

Figure 1 Schematic diagram of the hybrid workflow

trapping mechanisms. It supports comprehensive evaluation of CO_2 migration patterns, oil recovery performance and long-term geological storage reliability.

Conclusions

1. Field and laboratory CO_2-EOR studies have verified that enhancing the miscible interaction between injected CO_2 and crude oil can delay the arrival of gas breakthrough and effectively boost reservoir oil productivity. Numerical simulation results(Fig.2) show that fully miscible flooding achieves a final oil recovery rate of 40.58%, which surpasses the near-miscible and immiscible flooding cases by 25% and 49% respectively. Despite retaining the largest quantity of CO2 in subsurface formations under miscible operating conditions, the overall storage efficiency decreases by 23% in contrast to low-miscibility development modes. This distinct performance discrepancy indicates an inherent competitive relationship between hydrocarbon recovery efficiency, carbon sequestration scale and storage quality. It is therefore essential to tailor on-site injection schemes to coordinate economic production benefits and geological carbon storage effects.

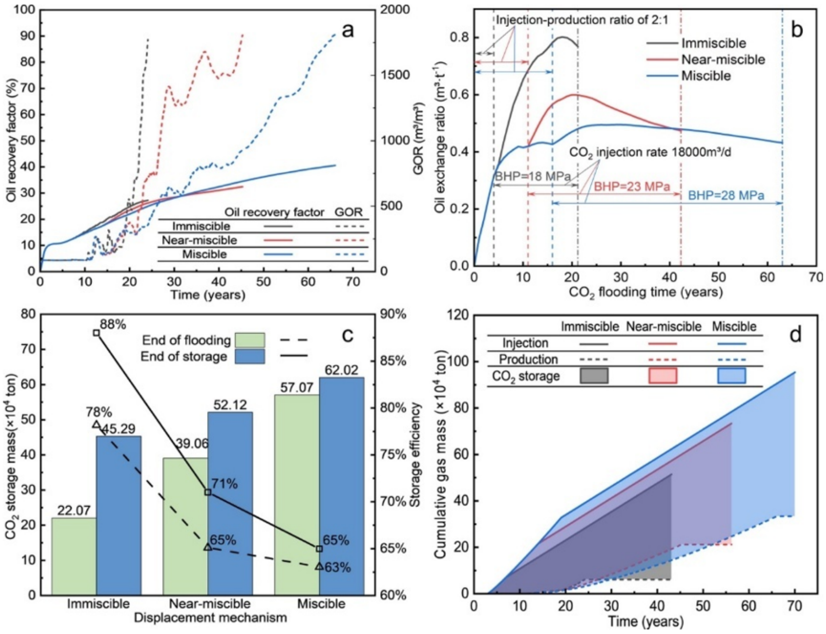

Figure 2 Comparison of the production and carbon sequestration performance of CO_2 flooding under diverse miscibility states. The evaluated indicators cover the oil recovery factor and gas-oil ratio (GOR), oil exchange coefficient, total sequestered CO_2 mass and corresponding storage effectiveness, as well as the cumulative volume of injected and produced CO_2.

2. The miscibility level of CO_2-oil mixtures is a decisive factor reshaping the spatial distribution and dynamic conversion of CO_2 trapping

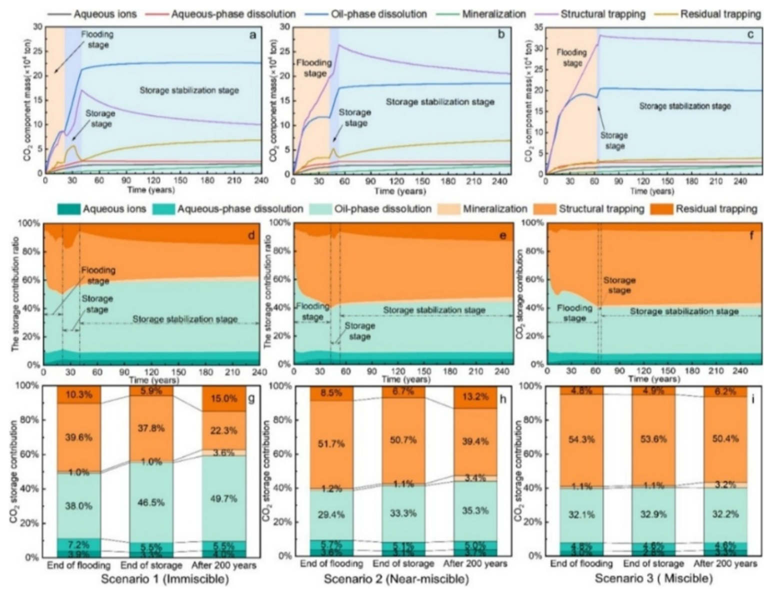

Figure 3 Time-dependent variations in stored CO_2 mass and the proportional contribution of six typical carbon sequestration forms across three miscibility scenarios, with subgraphs corresponding to immiscible (a, d, g), near-miscible (b, e, h) and miscible (c, f, i) flooding conditions.

forms in fractured low-permeability reservoirs. Improved miscibility during CO_2 flooding alters the dominant carbon fixation pathway, shifting the primary trapping mechanism from oil-phase dissolution and residual gas entrapment toward geological structural trapping (Fig.3). After a 200-year post-injection geological stabilization period, miscible flooding reduces oil-dissolved CO_2 content by 17.5% and residual gas trapping capacity by 8.8%, while elevating the contribution of structural trapping by 28.1%, compared with immiscible flooding treatments.

3. High-miscibility CO_2 flooding expands the low-pH aqueous zone in reservoir formation water and intensifies subsurface fluid-rock geochemical interactions. The acidic environmental conditions facilitate the dissolution of anorthite and clinochlore within rock formations. Meanwhile, such geochemical reactions trigger the precipitation of various primary rock minerals including quartz, kaolinite, dolomite, illite and K-feldspar, as well as secondary carbonate minerals such as magnesite and calcite (Fig.4).

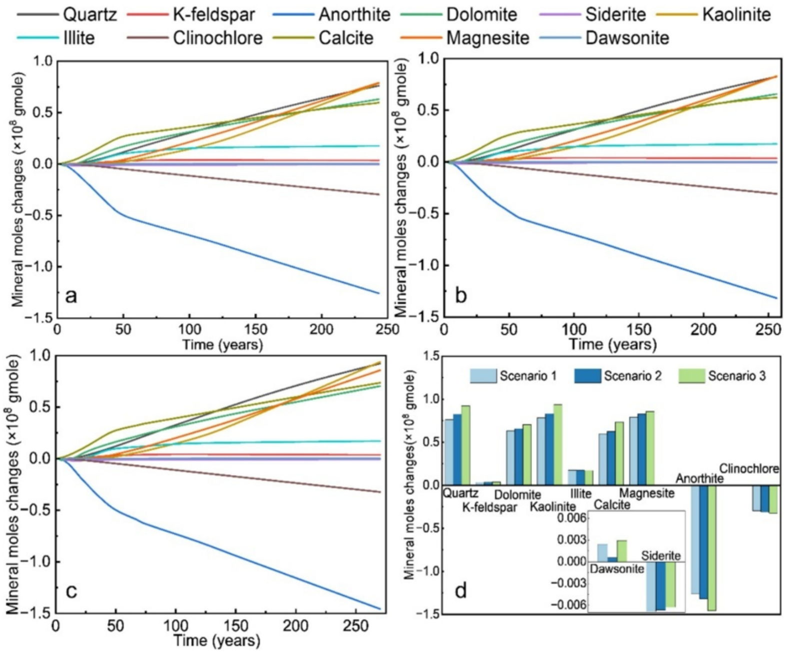

Figure 4 Molar variation characteristics of reservoir primary and secondary minerals under three CO_2 flooding schemes, including immiscible, near-miscible and miscible flooding scenarios, and a quantitative comparison of mineral alteration degrees among different development modes.

4. Mineral alteration activities primarily induce regional heterogeneity in reservoir physical properties. Precipitation-derived minerals are predominantly distributed within fracture systems, whereas mineral dissolution behaviors mainly occur in the tight reservoir matrix. In comparison, formation compaction acts as the core driving factor dominating long-term reservoir petrophysical evolution. In the post-injection stabilization phase, continuous formation pressure depletion leads to the deterioration of porosity and permeability in both fractures and matrix media, with the matrix system exhibiting more significant property attenuation. These geomechanical and geochemical variations strengthen the reservoir's sealing capacity, greatly improving the long-term geological stability and security of subsurface CO_2 sequestration (Fig.5).

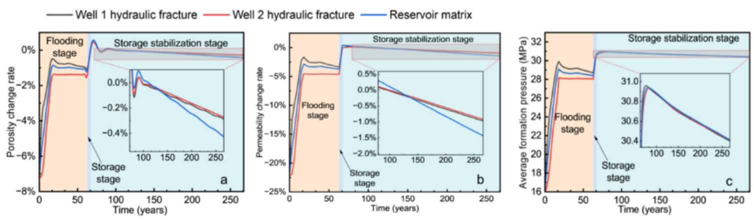

Figure 5 The combined influences of formation compaction and mineralization on petrophysical properties of hydraulic fracture networks and reservoir matrix, reflected in the variation rates of porosity and permeability as well as the dynamic changes of average formation pressure.

Overall, this study delivers targeted technical references for the implementation of CCUS projects in fractured low-permeability reservoirs. To achieve a balanced performance between oil production efficiency and carbon storage potential, field injection parameters should be optimized to guarantee at least near-miscible flooding states. Long-term monitoring of formation pressure fluctuations and geomechanical evolution is also indispensable, given the dominant role of formation compaction in maintaining reservoir sealing integrity over decades. Future research efforts can be directed toward the numerical characterization of stochastic natural fracture networks, multi-objective parameter optimization covering economic profit, environmental protection and operational safety, and the influence of impure CO_2 injection on the comprehensive performance of coupled CO_2-EOR and geological storage systems.

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