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Original Paper

Research Progress and Outlook on the Mechanism of Non-Uniform Utilization in Supercritical CO_2 Flooding Development of Shale Reservoirs

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Abstract

Supercritical CO_2 flooding technology for shale reservoirs represents a key approach to achieving efficient, low-carbon development. However, its effectiveness is significantly constrained by reservoir heterogeneous mobilization phenomena. This paper aims to review research progress and future prospects in this field. Supercritical CO_2 enhances recovery rates through core mechanisms including viscosity reduction, expansion, extraction, and improvement of reservoir physicochemical properties. However, geological mechanical heterogeneity, complex fracture networks, and nanopore variations collectively induce non-uniformity in the mobilization process. Macroscopically, CO_2 tends to migrate along high-permeability zones and fractures, leaving distant matrix oil poorly mobilized. Microscopically, disparities in transport capacity between organic and inorganic pores, coupled with diffusion-seepage coupling mechanisms, create pore-scale mobilization imbalances. Current research integrates multi-scale approaches including physical experiments, numerical simulations, and field monitoring, yet challenges persist such as unclear multi-field coupling mechanisms and difficulties in in-situ nanoscale observation. Future studies should focus on deepening understanding of multi-physics coupling mechanisms, developing intelligent and precise predictive models, and exploring integrated enhancement technologies to advance balanced mobilization and commercial development of shale reservoirs.

Keywords

supercritical carbon dioxide, shale oil, throughput development, heterogeneous utilization, enhanced oil recovery

1. Introduction

The growing global energy demand coupled with the depletion of conventional oil and gas resources has propelled the exploration and development of unconventional resources to the forefront. Shale reservoirs, with their vast reserves, have become a crucial strategic successor for ensuring global energy security. However, the ultra-low porosity and permeability characteristics of shale reservoirs necessitate large-scale hydraulic fracturing for commercial development. Post-fracturing, the matrix, bedding planes, and fractures form a complex multiscale flow network, resulting in highly heterogeneous reservoirs. The unique nature of shale reservoir development poses significant technical challenges for CO_2 enhanced oil recovery (EOR) technologies. Research gaps exist in understanding the interaction mechanisms between CO_2 and shale, CO_2 diffusion mechanisms under confined conditions, and CO_2 mobility control mechanisms in multiscale multiphase flows. These deficiencies lead to operational difficulties during actual implementation.-shale interaction mechanisms, CO_2 diffusion mechanisms under confined conditions, and CO_2 mobility control mechanisms in multiphase flow across scales. This lack of understanding hinders practical implementation, particularly regarding CO_2's impact on shale reservoir porosity and permeability parameters, its effective working distance within reservoirs, and directional control issues, thereby affecting field operation effectiveness (Wang Xubo, Xia Zhizeng, Liu Mengqi, et al., 2025).

Against this backdrop, carbon dioxide (CO_2) enhanced oil recovery (EOR) technology, particularly supercritical CO_2 Huff-n-Puff technology, demonstrates significant application potential. Supercritical CO_2 (temperature >31.1°C, pressure >7.39 MPa) combines the high diffusivity of a gas with the strong solubility of a liquid. It effectively reduces crude oil viscosity, significantly swells oil volume, extracts light hydrocarbon fractions, and interacts with shale to improve reservoir wettability and pore structure. Compared to continuous CO_2 injection displacement, the Huff-n-Puff mode is more suitable for low-permeability tight reservoirs, avoiding premature gas migration and offering flexible single-well operations. It is recognized as a strategic technology for secondary recovery in shale reservoirs (Tao Jiaping, Meng Siwei, Gong Changping, et al., 2024).

However, both field practice and laboratory studies indicate that SC-CO_2 flooding exhibits significant spatial heterogeneity. That is, substantial variations in crude mobilization and production enhancement occur between different production wells, between distinct fracture clusters within the same well, and even at the microscopic pore scale. This phenomenon of "uneven mobilization" results in some reservoir spaces being efficiently flushed while other areas remain largely untouched. This severely limits overall recovery rate improvement and impacts the technology's economic viability. Therefore, systematically investigating the heterogeneous mobilization mechanisms in supercritical CO_2 flood development of shale reservoirs, deeply revealing its dominant controlling factors and dynamic evolution patterns, holds crucial theoretical significance and engineering guidance value for optimizing injection-production parameters, predicting development dynamics, and ultimately achieving balanced and efficient mobilization of shale oil reservoirs (Xue Chunlong, 2024; Zhang Wei, 2024; Zhang Zhichao, Bai

Mingxing, & Du Siyu, 2024).

2. Fundamental Interactions between Supercritical CO_2 and Shale Reservoirs/Fluids

The essence of enhancing shale oil recovery through supercritical carbon dioxide (SC-CO_2) flooding technology lies in the complex series of physical, chemical, and mechanical interactions it undergoes with shale reservoirs and their contained fluids under reservoir temperature and pressure conditions. These interactions collectively alter crude oil's physical properties, phase behavior, and transport capacity within nanopores, while profoundly affecting the reservoir rock's physical structure and flow characteristics. Together, they form the physicochemical foundation for heterogeneous exploitation of shale oil. A deep understanding of these fundamental interactions is essential for elucidating macro- and micro-scale heterogeneous exploitation mechanisms.

Supercritical CO_2 occupies a unique intermediate phase between gas and liquid, exhibiting liquid-like density while possessing gas-like viscosity and diffusion coefficients. This dual nature endows it with both the strong permeation capacity of a gas and the exceptional solubility of a liquid. Upon injection into shale reservoirs, SC-CO_2 first interacts with the in-situ crude oil. It exhibits exceptional extraction and dissolution capabilities for light and intermediate hydrocarbon fractions, significantly reducing crude oil viscosity—sometimes by several orders of magnitude—and greatly enhancing its flowability (Li Xiaofeng, 2023). Concurrently, substantial CO_2 dissolution within the oil causes significant volume expansion, with expansion rates ranging from 10% to 70% or higher. This expansion not only increases the crude oil's internal energy but, more critically, overcomes capillary forces, "squeezing" the oil out of finer pores. This mechanism is one of the key drivers for mobilizing oil confined within nanopores. Furthermore, when reservoir pressure reaches or exceeds the minimum miscibility pressure (MMP), CO_2 and crude oil undergo multiple phases of contact miscibility, causing interfacial tension to approach zero. This dramatically eliminates resistance to crude oil flow (Hou Guifeng, 2023).

These effects on fluids do not occur in isolation but complement SC-CO_2's transformation of the shale rock itself. Shale is a highly complex heterogeneous medium composed of organic matter (kerogen), inorganic minerals (e.g., quartz, clays, carbonates), and multiscale pores. Chemical reactions between SC-CO_2 and these diverse components are crucial. Most notably, SC-CO_2 exhibits a significant dissolution effect on carbonate minerals like calcite and dolomite. When dissolved in formation water to form carbonic acid, SC-CO_2 dissolves these minerals, enlarging pore throats, enhancing connectivity, and even inducing new microfractures at mechanically weak points—creating fresh pathways for crude oil flow. On the other hand, SC-CO_2 exhibits strong adsorption affinity for organic kerogen. This competitive adsorption can displace crude oil originally adsorbed onto the pore surfaces of organic matter. More critically, SC-CO_2 adsorption alters the wettability of rock surfaces. Shale typically exhibits oil-wet or mixed-wet properties, which significantly constrain crude oil recovery rates. SC-CO_2 can reverse the rock surface from oil-wetting to intermediate or even gas-wetting, significantly reducing capillary resistance to crude oil flow and promoting its detachment from pore surfaces (Zhang Zhichao, Li Honglei, Yu Chunyong, et al., 2023).

Beyond chemical interactions, physical-mechanical effects are equally significant. During injection, high-pressure SC-CO_2 alters the local stress field distribution near the wellbore. This stress disturbance may reopen or extend natural fractures, or induce new microfracture networks in brittle rocks, thereby expanding the effective oil-discharge volume. However, this process is strongly influenced by reservoir heterogeneity. Stress field alterations are often non-uniform, setting the stage for subsequent non-uniform CO_2 absorption and crude oil mobilization.

All these interactions occur against an extremely heterogeneous backdrop—the multiscale heterogeneity of shale reservoirs. Mineralogically, carbonate-rich zones are more susceptible to dissolution, while clay mineral zones may experience swelling or particle migration, clogging pore throats. In terms of pore structure, the organic pore network is characterized by strong adsorption and nanoscale dimensions, while inorganic pores may offer relatively better flow pathways. The distribution of crude oil within pores is also heterogeneous, with oil existing both as adsorbed oil within organic matter and as free oil in inorganic pores and macropores. SC-CO_2 transport mechanisms differ significantly across media: in macroscalar fractures and macropores, pressure-driven seepage dominates; whereas in nanoscale organic pore networks, molecular diffusion becomes the primary transport mechanism, occurring at rates substantially slower than seepage.

This intricate interplay among reservoir, fluid, and SC-CO_2 constitutes a prototypical thermo-hydro-mechanical-chemical (THMC) multi-field coupled system. Fluid flow and mass transfer are influenced by stress field variations, while reaction rates and scope depend on temperature and flow patterns. Conversely, mineral dissolution and precipitation induced by chemical reactions permanently alter rock mechanics and pore architecture. It is precisely the nonlinear response of this multi-field coupled system that determines the dynamic distribution and efficiency of SC-CO_2 in reservoirs, ultimately leading to the non-uniform mobilization of crude oil both spatially (from fractures to matrix, from macro to micro scales) and temporally (across different production cycles). Therefore, elucidating these fundamental interactions is the cornerstone for constructing any predictive model and optimizing development strategies.

3. Research Progress on Mechanisms of Non-Uniform Recovery

The heterogeneous mobilization observed during supercritical CO_2 flooding arises from complex mechanisms involving the interplay of geological conditions, fluid properties, engineering operations, and multi-physics coupling. In recent years, researchers have progressively revealed the dominant factors and operational processes underlying this phenomenon through physical experiments, numerical simulations, and field practices. Research progress has primarily focused on two dimensions—macro and micro—with increasing emphasis on the comprehensive effects of multi-field coupling.

At the macroscale, non-uniform mobilization is primarily governed by the inherent geomechanical heterogeneity of reservoirs. Shale reservoirs exhibit highly spatially non-uniform distributions of mineral composition, cement strength, natural fracture networks, and in-situ stress fields. During supercritical CO_2 injection, this heterogeneity induces pronounced "dominant pathway" effects. As an extremely mobile fluid, CO_2 invariably follows paths of least resistance. It tends to preferentially enter high-permeability macrofractures, microfracture zones, or relatively loose lithologic bands, forming high-velocity flow channels while bypassing dense, low-permeability matrix blocks. This "finger-like" and "gas-like" phenomenon confines a substantial portion of injected CO_2 to circulate within a limited high-permeability network. It fails to effectively penetrate and displace crude oil within low-permeability matrix, resulting in extreme unevenness in the macroscale mobilization range. Secondly, the non-uniform distribution of in-situ stress profoundly influences the CO_2 injection front. During the injection phase, the high-pressure fluid injection locally alters the stress state of the formation, creating a "stress shadow" effect. CO_2 is more readily absorbed in regions with lower current in-situ stress. Conversely, reservoirs under high stress shadows—particularly matrix zones fragmented by complex fracture networks—remain poorly penetrated by CO_2, resulting in mobilization patterns exhibiting strong anisotropy closely correlated with stress distribution. Furthermore, the coordination between artificially fractured networks and wellbore geometry is another critical factor. A successful fracturing operation generates multiple fracture clusters, yet significant variations exist in their flow capacity, extension length, and connectivity with natural fractures. This leads to uneven distribution of injected CO_2 among fracture clusters, with some acting as primary fluid entry/exit points while others contribute minimally. Consequently, the oil displacement volumes controlled by individual fractures vary greatly, creating heterogeneity in reservoir mobilization around the wellbore (Fan Lingyi, 2022; He Mengqing, 2022; Zhu Zhuangying, 2022; Fan Lingyi & Li Baoting, 2022).

At the microscopic level, the heterogeneous mobilization mechanism becomes even more intricate and complex, rooted in the extreme complexity of the shale nanopore system. Shale pore space consists of a mixture of organic pores and inorganic pores, which exhibit fundamental differences in surface properties, pore size distribution, and transport mechanisms. Organic pores exhibit strong hydrophobicity and potent adsorption capacity for hydrocarbons, but their extremely small pore sizes (typically nanoscale) impose substantial flow resistance. While supercritical CO_2 can effectively displace crude oil adsorbed on organic surfaces through competitive adsorption, mass transfer within these pores primarily relies on slow molecular diffusion. In contrast, inorganic pores (e.g., quartz, carbonate dissolution pores) exhibit weaker surface affinity but larger pore sizes and superior permeability. This difference in transport mechanisms (diffusion-dominated vs. flow-dominated) and efficiency results in varying sequences and degrees of crude oil recovery across different pore types, known as micro-scale heterogeneity. Additionally, phase behavior and non-miscibility effects at the pore scale further exacerbate this heterogeneity. Minor fluctuations in reservoir pressure can cause local switching between miscible and immiscible states within the CO_2–crude oil system. Near the minimum miscible pressure, local pressure differentials may enable highly efficient miscible extraction in certain pores, while adjacent regions may remain in less efficient immiscible displacement, forming a "patchy" micro-scale recovery pattern (Zhu

Zhuangying, 2022; Fan Lingyi & Li Baoting, 2022; Shang, D. M., Wu, J., Jia, B., et al., 2021).

Notably, macro- and micro-mechanisms do not operate independently but are tightly intertwined through thermo-hydro-mechanical-chemical (THMC) multiphase coupling processes. For instance, heat exchange between injected low-temperature CO_2 and the formation alters local temperature fields, which in turn affect crude oil viscosity, CO_2 solubility, and chemical reaction rates. Chemical reactions (e.g., carbonate dissolution) alter pore structure, thereby modifying local permeability and stress fields. Changes in stress fields then feed back to influence fluid flow paths. This constitutes a highly nonlinear dynamic process. Multiple flooding cycles cause these coupled effects to continuously evolve, typically resulting in a dynamically expanding mobilization zone. The initial cycle primarily mobilizes crude oil near the wellbore and in high-permeability fractured zones. As cycles increase, CO_2 gradually diffuses and slowly infiltrates into more distant matrix regions, expanding the mobilized area. However, its inherent non-uniformity persists, with the mobilization front continuously shifting and evolving.

In summary, the non-uniform mobilization in supercritical CO_2 flooding represents a multi-scale systemic issue. Macro-scale geomechanical control and micro-scale pore network/mass transfer limitations jointly form its core mechanisms, while dynamic coupling across multiple physical fields determines its complex spatiotemporal evolution patterns. Current research is shifting from single-mechanism analysis toward integrated approaches, aiming to more accurately reveal and predict this complex process by coupling macro- and micro-scale models. This provides theoretical support for achieving balanced and efficient development.

4. Challenges and Outlook

As a key method for developing shale reservoirs, supercritical CO_2 flooding technology shows promising applications but still faces numerous challenges in both fundamental research and practical implementation. Current research limitations primarily stem from insufficient understanding of multi-field coupling mechanisms. The migration and recovery of supercritical CO_2 in shale reservoirs constitute a complex process involving full coupling of thermal, fluid, mechanical, and chemical phenomena, characterized by strong nonlinear interactions among physical fields. Existing studies predominantly focus on single processes or dual-field coupling, lacking quantitative descriptions of the dynamic behavior of fully coupled systems and their control mechanisms over heterogeneous recovery patterns. Second, experimental techniques face significant bottlenecks, particularly in nanoscale in-situ observation. Achieving dynamic visualization monitoring of phase transitions within pores, interfacial behavior, and mass transfer processes under real-world formation temperature and pressure conditions remains an urgent technical challenge. In numerical simulation, core obstacles to constructing high-precision predictive models include achieving seamless multiscale coupling from nanopores to fracture networks and efficiently integrating multiple physical processes while fully accounting for reservoir heterogeneity (Zhu, Chao Fan, 2020). Furthermore, translating mechanistic understanding into economically viable engineering solutions—optimizing throughput parameters to maximize balanced utilization volume while controlling CO_2 procurement and injection costs—presents a critical economic challenge constraining commercial application.

To address these challenges, future research should pursue breakthroughs in several key directions. The primary task is to deepen the study of multi-field coupling mechanisms, establishing a comprehensive theoretical framework for fully coupled THMC (Thermal-Hydraulic-Mechanical Coupling), particularly elucidating chemical-mechanical feedback mechanisms and the influence of thermal effects. Technological innovation is the critical breakthrough point, requiring the development of next-generation high-pressure, high-temperature microscopic visualization experimental apparatus. Leveraging large-scale scientific facilities such as synchrotron radiation will enable in-situ observation at the nanoscale. Simultaneously, artificial intelligence and machine learning methods should be vigorously integrated to leverage their strengths in handling high-dimensional nonlinear problems, extracting patterns from massive datasets, constructing efficient surrogate models, and optimizing historical recovery and development predictions. Development approaches should advance integrated geological-engineering intelligent optimization, dynamically updating geological models based on real-time monitoring data and employing intelligent algorithms to achieve personalized "one reservoir, one strategy" development (Shang Shengxiang, 2018). Finally, synergistic effects between supercritical CO_2 flooding and other technologies should be explored. This includes combining it with nanofluid enhancement, reservoir pressurization, or efficient plugging agents to block dominant flow pathways and redirect CO_2 toward untapped zones, thereby proactively addressing non-uniform recovery through technical means. Through multidisciplinary integration and innovation, overcoming the challenge of non-uniform recovery and achieving efficient shale reservoir development is ultimately achievable.

5. Conclusions

The mechanism of heterogeneous mobilization during supercritical CO_2 flooding in shale reservoirs is a core scientific issue determined by reservoir multiscale heterogeneity, complex fluid phase behavior, and multiphysics coupling. This review indicates that macro-scale geological mechanical variations, non-uniform fracture network distribution, and micro-scale pore structure differentiation alongside competing transport mechanisms (diffusion and seepage) are intrinsic causes of mobilization heterogeneity. The nonlinear interactions within the fully coupled thermal-fluid-mechanical-chemical process further exacerbate this spatial heterogeneity and dynamic evolution of fluid mobilization. Current research, integrating physical experiments, numerical simulations, and field monitoring, has revealed some key mechanisms. However, significant challenges remain in developing fully coupled theories, achieving nanoscale in-situ characterization, and establishing high-precision predictive models. Future breakthroughs require multidisciplinary innovation, integrating advanced experimental techniques, artificial intelligence, and integrated geotechnical engineering design. Proactive regulation of flow profiles through developing synergistic enhancement technologies is essential. Ultimately, overcoming heterogeneous flow challenges is critical for achieving efficient, low-carbon shale oil resource development and serves as the theoretical foundation for advancing this technology toward large-scale industrial application.

References

Fan Lingyi, & Li Baoting. (2022). Current Status and Prospects of CO_2 Injection for Enhanced Recovery in Shale Reservoirs. *Petrochemical Application*, *41*(02), 1-7.

Fan Lingyi. (2022). *Experimental and Numerical Simulation Study on CO_2 Injection for Enhanced Recovery in Shale Oil Reservoirs*. Xi'an Petroleum University.

He Mengqing. (2022). *Study on Fracture Propagation Behavior and Micro-Mechanism of CO_2 Fracturing in Shale Reservoirs*. China University of Petroleum (Beijing).

Hou Guifeng. (2023). *Research on Mechanism and Optimization Design of CO_2 Injection for Enhanced Recovery in Shale Reservoirs*. Northeast Petroleum University.

Li Xiaofeng. (2023). *Preparation and Performance Study of CO_2 Micro-Nano Dispersion Systems for Enhancing Shale Reservoir Recovery Rate*. China University of Petroleum (Beijing).

Shang Shengxiang. (2018). *Study on Enhanced Shale Oil Recovery Using Supercritical CO_2 and Solvent-Assisted Miscible Phase*. China University of Petroleum (East China).

Shang, D. M., Wu, J., Jia, B., et al. (2021). Prospects for the Application of Supercritical CO_2 in the Development of Terrestrial Shale Oil Reservoirs. *Contemporary Chemical Industry*, *50*(07), 1650-1653.

Tao Jiaping, Meng Siwei, Gong Changping, et al. (2024). Feasibility Study on Pre-fracturing with CO_2 in Pure Shale Reservoirs. Shanghai Joint Unconventional Energy Research Center, Shanghai Science and Technology Exchange Center. *Proceedings of ECF2024: The 14th Asia-Pacific Shale Oil & Gas and Unconventional Energy Conference*. China Petroleum Exploration and Development Research Institute; Daqing Oilfield Co., Ltd.; 2024, 197-202.

Wang Xubo, Xia Zhizeng, Liu Mengqi, et al. (2025). Prediction of CO_2 Injection Effects in Shale Reservoirs: A Case Study of Representative Wells in the BK Block. *Petroleum and Chemical Equipment*, *28*(01), 12-14+20.

Xue Chunlong. (2024). *Micro-Mechanism Study on CO_2 Enhanced Recovery in Shale Oil Reservoirs*. Shandong University.

Zhang Wei. (2024). *Numerical Simulation of Near-Wellbore Four-Dimensional Stress During CO_2 Twinning Development in Shale Reservoirs*. Xi'an Petroleum University.

Zhang Zhichao, Bai Mingxing, & Du Siyu. (2024). Study on Pore Mobilization Characteristics During CO_2 Injection Drive in Shale Reservoirs. *Reservoir Evaluation and Development*, *14*(01), 42-47.

Zhang Zhichao, Li Honglei, Yu Chunyong, et al. (2023). Research Progress on CO_2 Development of Shale Reservoirs. *Oilfield Chemistry*, *40*(03), 543-549.

Zhu Zhuangying. (2022). *Study on the Mechanism of Supercritical CO_2 Stripping of Shale Oil*. Chongqing University.

Zhu, Chao Fan. (2020). *Study on CO_2 Injection for Enhanced Recovery in Shale Reservoirs*. China University of Petroleum (East China).