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Fundamental Experimental Study on Hot CO_2 Fluid Injection in Ultra-Deep Heavy Oil Reservoirs (ICCUSC2025)

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ABSTRACT

The development of ultra-deep heavy oil reservoirs currently faces challenges including steam injection difficulties, poor fluid mobility, and significant thermal losses in oil layers. The target reservoir had undergone various enhanced oil recovery (EOR) methods such as steam thermal recovery and viscosity reducer huff-and-puff stimulation. However, none of these approaches had achieved breakthrough in productivity. This highlights the critical importance of exploring hot CO_2 fluid injection technology specifically tailored for ultra-deep heavy oil reservoir development. This study systematically conducted the following experimental investigations: (1) Three-stage (10 %, 30 %, 60 %) CO_2 gas injection expansion experiments with heavy oil, coupled with rheological characterization under varied temperature-pressure conditions. (2) Precise measurements of CO_2 diffusion coefficients and solubility parameters in heavy oil systems, including thermal conductivity determination across temperature/pressure gradients. (3) Experimental analysis of pressure-time dependent CO_2 extraction effects on heavy oil component fractionation. (4) Microscopic visualization experiments elucidating the CO_2 displacement mechanisms in ultra-deep heavy oil reservoirs at pore-scale resolution. Experimental observations revealed that increasing the CO_2 injection ratio leads to a systematic decrease in crude oil density (from 1.0646 to 0.9863 g/cm³ at 100 °C) accompanied by a 4.65-12.47 % expansion in volume coefficient. The native heavy oil exhibited shear-thinning behavior consistent with the Herschel-Bulkley model, whereas CO_2-saturated samples transitioned to Newtonian flow characteristics with viscosity reductions exceeding 75 % at 10 s^{-1} shear rate. Notably, diffusion coefficients in ultra-deep heavy oil reservoirs (depth > 2000 m, viscosity > 1×10^4 mPa•s) were measured to be approximately one order of magnitude lower than those in conventional crude oil. Thermal conductivity analysis of the CO_2-heavy oil mixture showed progressive reductions with elevated temperature and pressure. Compositional monitoring identified selective extraction of C_5–C_7 hydrocarbons during initial CO_2 interaction, while higher carbon-number components (C_{12}–C_{20}) required increased pressure for effective mobilization. The pressure-driven enhancement of CO_2 extraction efficiency in ultra-deep heavy oil necessitated extended contact durations (> 24 h) to reach equilibrium. In the process of heavy oil displacement, CO_2 was prone to gas channeling, while CO_2+synergist had the effect of emulsifying and dissolving viscosity reduction and forming foam oil to expand sweep efficiency in the process of displacement.

Keywords: Ultra-deep; heavy oil; supercritical CO_2; thermal-CO_2 synergistic; mechanism of action

NONMENCLATURE

Abbreviations	
EOR	enhanced oil recovery
CSS	cyclic steam stimulation
ASP	alkaline-surfactant-polymer
GOR	gas-oil ratio
FVF	formation volume factor

1. INTRODUCTION

The relentless pursuit of energy resources places immense pressure on the oil and gas industry to maximize recovery from ever-difficult-to-produce reserves. Among these, the development of ultra-deep heavy oil reservoirs represents one of the most

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challenging frontiers. Characterized by depths often exceeding 2000 meters and oil viscosities routinely surpassing 10000 mPa·s at reservoir conditions, these deposits hold significant volume but are notoriously difficult to exploit economically. The very properties that make heavy oil valuable also render it stubbornly immobile under natural driving forces[1]. Conventional production methods quickly hit diminishing returns, necessitating the deployment of enhanced oil recovery (EOR) techniques to unlock the remaining resources. However, as the industry pushes deeper, the effectiveness and applicability of traditional EOR methods are being severely tested, demanding innovative solutions[2].

The most established thermal method for heavy oil recovery is steam injection, primarily cyclic steam stimulation (CSS) or steam flooding. This technique relies on the injection of high-temperature steam to heat the reservoir rock and the viscous oil, thereby reducing oil viscosity, improving its mobility, and mobilizing trapped fluid segments[3]. While CSS has proven successful in shallower reservoirs (e.g., the Kern River field in California), its application in ultra-deep reservoirs faces multiple critical hurdles. Firstly, the immense depth translates directly to significant pressure losses during steam injection. Overcoming these requires either unrealistically high surface pressures or impractically long tubing lengths, both impacting operational safety, cost, and potential damage to the reservoir near the wellbore (near-wellbore damage)[4-6]. Secondly, heat transfer efficiency becomes a major bottleneck. Deep reservoirs are often surrounded by formations with lower thermal conductivity, creating a 'cold finger' effect where heat is rapidly lost laterally or vertically before reaching the production zone. This results in substantial thermal losses, requiring vast amounts of surface steam to maintain effective downhole temperatures, which drastically increases operational costs and can lead to environmental concerns regarding water and energy consumption[7]. Thirdly, the high viscosity of deep heavy oil poses a fundamental challenge. Even when heated, the oil's inherent resistance to flow remains high, leading to poor fluid mobility and difficulties in efficiently drawing oil towards the production wells, often resulting in early breakthrough of the injected steam or inefficient sweep patterns. Furthermore, scaling up these operations to achieve commercial production rates in deep, potentially heterogeneous reservoirs remains a significant engineering challenge.

Recognizing the limitations of thermal methods, the industry has explored other EOR mechanisms, particularly those based on chemical flooding. Viscosity reduction chemicals (often polymers or surfactants), sometimes combined with alkali (alkaline-surfactant-polymer, ASP), aim to alter the oil's physical properties or modify the fluid-rock interactions to enhance displacement efficiency[8, 9]. While these methods show promise in certain heavy oil scenarios, their performance in ultra-deep, high-viscosity environments has been inconsistent. The extreme pressure and temperature conditions deep within the reservoir can significantly impact the effectiveness of chemical agents–polymers may degrade, surfactants might lose their efficiency, and complex interactions with the geological formation (e.g., salinity, mineralogy) can be difficult to predict and optimize. Moreover, achieving uniform distribution and sufficient contact time deep within the reservoir formation presents its own set of challenges[10]. In the specific case mentioned, despite the application of both steam thermal recovery and viscosity reducer huff-and-puff stimulation, productivity breakthrough – defined as a significant and sustainable increase in oil production beyond what is achievable with primary or conventional secondary methods–has remained elusive. This persistent lack of success underscores a critical gap in our understanding and the need for technology specifically tailored to overcome the unique challenges posed by these extreme reservoir conditions.

Given these limitations, the search for alternative EOR mechanisms becomes paramount. Carbon dioxide (CO_2) injection has emerged as a highly promising contender, particularly for heavy oil recovery. CO_2 offers several distinct advantages over traditional steam or chemical methods. Its relatively low molecular weight allows for deeper penetration into the reservoir compared to steam. It exhibits superior miscibility with many heavy oils at reasonable injection conditions, leading to efficient oil swelling, viscosity reduction, and improved microscopic displacement mechanisms (miscible flooding)[11]. Furthermore, CO_2 is readily available, often captured from industrial sources (opening pathways to carbon sequestration alongside EOR), and its environmental profile is generally considered more favourable than some other chemicals or energy-intensive processesp[12]. However, the direct application of CO_2 technology in ultra-deep heavy oil reservoirs requires careful re-evaluation and potentially significant modification. The extreme depths introduce unique operational considerations, including managing the high injection pressures required to overcome reservoir resistance, ensuring the CO_2 reaches the target zone effectively, and designing surface facilities

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accordingly[13]. More importantly, the fundamental physics and chemistry of CO_2 interaction with oil and rock change significantly under the high-pressure, high-temperature conditions prevalent in these deep reservoirs. Questions arise: Does CO_2 achieve the same level of miscibility? Are the viscosity reduction effects sufficient? How does heat transfer (or lack thereof) impact the process? Are the diffusion rates different? Standard correlations developed for shallower, conventional reservoirs may not apply.

This study was motivated by the specific challenges encountered in ultra-deep heavy oil reservoirs and the potential of CO_2 injection, but with the critical awareness that its application requires deeper investigation under these extreme conditions[14, 15]. We argue that simply applying surface-measured properties or correlations developed for shallower reservoirs to ultra-deep systems is inadequate and potentially misleading. The physics is different. Therefore, our research systematically investigates the performance and mechanisms of CO_2 injection specifically tailored for these demanding environments through a combination of rigorous experimental analysis and critical interpretation[16, 17].

This study systematically conducted the following experimental investigations: (1) Three-stage (10 %, 30 %, 60 %) CO_2 gas injection expansion experiments with heavy oil, coupled with rheological characterization under varied temperature-pressure conditions. (2) Precise measurements of CO_2 diffusion coefficients and solubility parameters in heavy oil systems, including thermal conductivity determination across temperature/pressure gradients. (3) Experimental analysis of pressure-time dependent CO_2 extraction effects on heavy oil component fractionation. (4) Microscopic visualization experiments elucidating the CO_2 displacement mechanisms in ultra-deep heavy oil reservoirs at pore-scale resolution.

2. MATERIAL AND METHODS

The crude oil used in this experimental study was taken from the crude oil produced by Ken 119 well in Shengli Oilfield. The crude oil has been dehydrated and degassed before use. The density of crude oil is 1.0646 g/cm^3 at 25 °C. The viscosity of crude oil is 4936 g/cm^3 at 100 °C. The reservoir has the characteristics of deep, thick, thin and sensitive. The buried depth is more than 2000 m, the viscosity of crude oil is more than 1×10^4 mPa · s, the thickness of oil layer is less than 6 m, and the permeability retention rate is less than 30 %. The formation pressure is 21.96 MPa.

This study systematically conducted the following experimental investigations: (1) Three-stage (10 %, 30 %, 60 %) CO_2 gas injection expansion experiments with heavy oil, coupled with rheological characterization under varied temperature-pressure conditions. (2) Precise measurements of CO_2 diffusion coefficients and solubility parameters in heavy oil systems, including thermal conductivity determination across temperature/pressure gradients. (3) Experimental analysis of pressure-time dependent CO_2 extraction effects on heavy oil component fractionation. (4) Microscopic visualization experiments elucidating the CO_2 displacement mechanisms in ultra-deep heavy oil reservoirs at pore-scale resolution.

3. RESULTS AND DISCUSSION

3.1 Mechanisms of Supercritical CO_2 Impact on the Physical Properties of Ultra-Deep Heavy Oil

3.1.1 CO_2 Expansion for Energy Enhancement in Heavy Oil—PVT Experiments

As the molar ratio of CO_2 injection increases, both the bubble point pressure and solution gas-oil ratio (GOR) rise.

When the molar ratio reaches 60.12 %, the bubble point pressure increases linearly by 12 MPa, and the solution GOR attains 92.07.

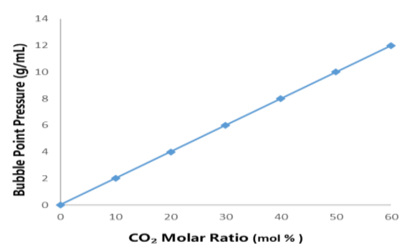

Fig.1. Bubble Point Pressure Trend of Heavy Oil vs. CO_2 Molar Ratio(20 MPa, 100 °C)

As the molar ratio of CO_2 injection increases, the density of crude oil decreases and the formation volume factor (FVF) rises after CO_2 dissolution.

When the CO_2 molar ratio reaches 60.12 %, the FVF increases from 1.0 to 1.1247, while the density declines from 1.06 g/cm³ to 0.9863 g/cm³.

3.1.2 CO_2 Effects: Viscosity Reduction and Enhanced Rheology of Heavy Oil– Rheology Experiments

Viscosity Reduction by CO_2 Dissolution: After CO_2 dissolves into heavy oil, the viscosity decreases significantly. At a CO_2 molar ratio of 60 %, the viscosity reduction rate reaches 78.64 %.

Temperature and CO_2 Effects on Rheology: Heavy oil viscosity is highly temperature-sensitive. The original

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heavy oil exhibits rheological behavior consistent with the Herschel-Bulkley model (a non-Newtonian fluid). However, with CO_2 addition, its behavior transitions to Newtonian fluid characteristics.

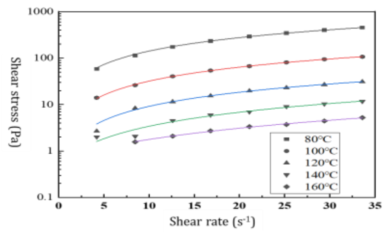

Fig.2. Rheology Curve of Heavy Oil

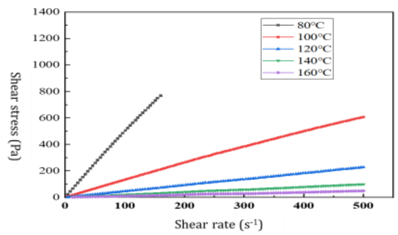

Fig.3. CO_2-Modified Heavy Oil Rheology Curve

At the same temperature and shear rate, the viscosity of heavy oil decreases with the increase of CO_2 pressure.

Under the same pressure and shear rate, the shear stress decreases significantly with the increase of temperature, and the viscosity decreases significantly.

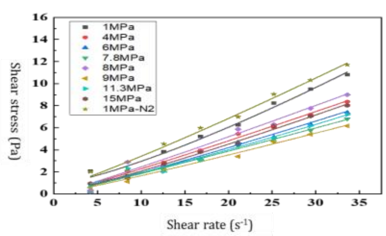

Fig.4. Rheological curves of heavy oil under different temperature conditions (140℃)

3.2 Mechanisms of Supercritical CO_2 Impact on the Physical Properties of Ultra-Deep Heavy Oil

3.2.1 Dissolution and Diffusion Characteristics of CO_2 in Ultra-Deep Heavy Oil

Based on the linear relationship between the pressure decay of CO_2 bulk phase and the square root of time, the diffusion coefficient of CO_2 in ultra-deep heavy oil was calculated by establishing a method for measuring the diffusion/dissolution of CO_2 in heavy oil under porous media conditions.

Fig.5. An experimental device for evaluating the diffusion/ dissolution performance of CO_2 in heavy oil based on pressure drop method

During the diffusion/dissolution process, the bulk pressure of CO_2 decreased continuously, and the bulk pressure change curve included two stages: rapid decline and slow decline.

The diffusion coefficient of CO_2 in ultra-deep heavy oil was about 10 times lower than that in ordinary crude oil, and some measures were needed to improve the diffusion rate.

The diffusion coefficient of CO_2 in heavy oil increased with the increase of temperature and decreased with the increase of pressure.

The equilibrium solubility of CO_2 in heavy oil decreased with the increase of temperature and increased with the increase of pressure.

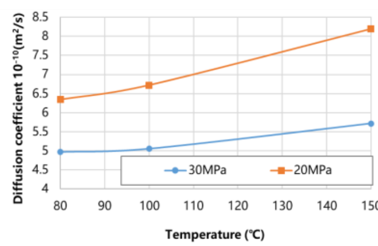

Fig.6. The diffusion coefficient curve of CO_2 in ultra-deep heavy oil under different temperature and pressure conditions

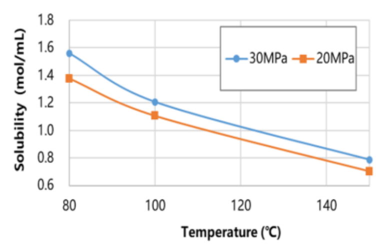

Fig.7. The dissolution coefficient curve of CO_2 in ultra-deep heavy oil under different temperature and pressure conditions

3.2.2 Dissolution and Diffusion Characteristics of CO_2 in Ultra-Deep Heavy Oil

The thermal conductivity of heavy oil under normal pressure was measured by transient plane heat source and line heat source, and the results were close.

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Compared with conventional heavy oil, the thermal conductivity of the target heavy oil was higher and increased with the increase of temperature.

According to the results of NIST database, the thermal conductivity of n-alkanes of C_{30}-C_{42} also increased with the increase of temperature. The experimental results of heavy oil composition chromatography showed that the content of C_{30}-C_{42} in crude oil was more than 40 %, so this was one of the reasons why the thermal conductivity of the target heavy oil increased with temperature.

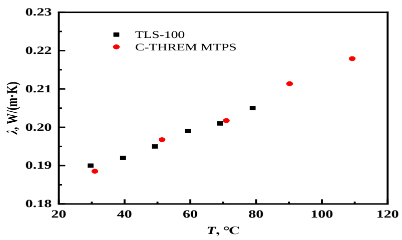

Fig.8. The variation curves of thermal conductivity of heavy oil with different temperatures under atmospheric pressure

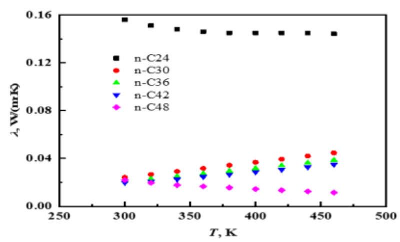

Fig.9. NIST database query results of n-alkanes

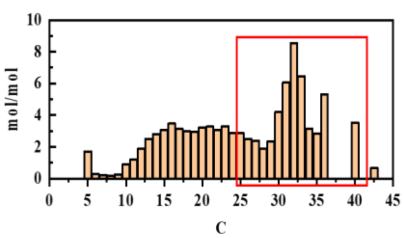

Fig.10. Heavy oil composition chromatogram

With the increase of temperature/pressure, the thermal conductivity of heavy oil-CO_2 decreased slowly.

The increase of temperature and pressure led to the decrease of thermal conductivity. This was because CO_2 dissolved in heavy oil and increased the intermolecular distance, thus reducing the thermal conductivity of heavy oil.

3.2.3 Effect of CO_2 extraction on the composition of ultra-deep heavy oil-different pressures and times

CO_2 could extract C_5~C_7 components in heavy oil, and the carbon number of crude oil components extracted after increasing pressure was higher, indicating that increasing pressure could enhance the supercritical CO_2 extraction effect.

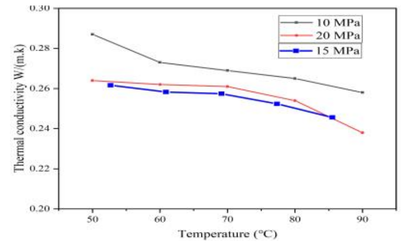

Fig.11. Under different pressures, the curve of thermal conductivity with temperature is obtained

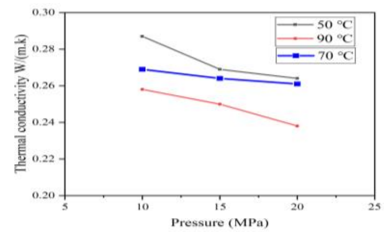

Fig.12. The variation curve of thermal conductivity with pressure at different temperatures

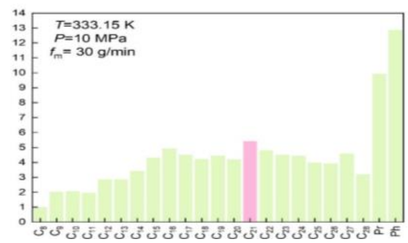

Fig.13. Changes of crude oil components after CO_2 extraction under 10 MPa

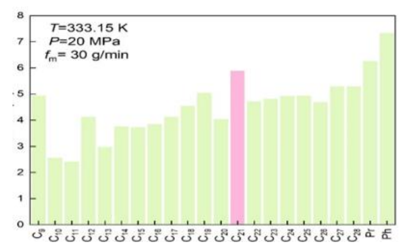

Fig.14. Changes of crude oil components after CO_2 extraction under 20 MPa

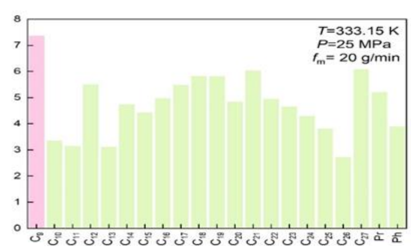

Fig.15. Changes of crude oil components after CO_2 extraction under 25 MPa

With the increase of the interaction time between heavy oil and CO_2, the signal of heavy oil decreased and the T_2 spectrum shifted to the left, indicating that the proportion of light components in heavy oil decreased and the proportion of heavy components increased.

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Pressure could improve the extraction of CO_2 and ultra-deep heavy oil, but this effect took a certain time.

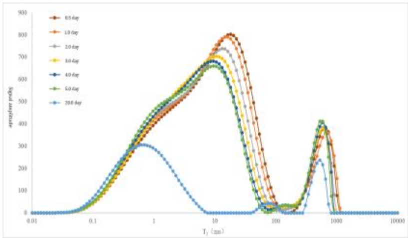

Fig.16. T2 spectra of supercritical CO_2 reacted with heavy oil for different time

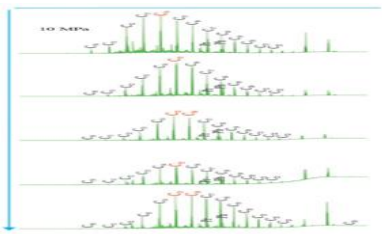

Fig.17. The total hydrocarbon chromatogram of crude oil after reaction of supercritical CO_2 with heavy oil for different time (10MPa)

3.3 Microscopic mechanism of supercritical CO_2 on ultra-deep heavy oil

After pure CO_2 flooding, the gas phase will become a discrete bubble state, and the remaining oil is mainly continuous and columnar.

After adding oil-soluble CO_2 synergist, CO_2 flooding can continue to use heavy oil in some large pores. In the later stage of CO_2 flooding, it is easy to form gas channeling, and the remaining oil is mainly cluster, columnar and membrane residual oil.

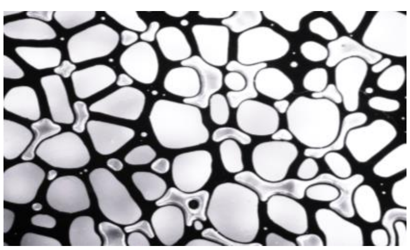

Fig.18. Residual oil distribution after pure CO_2 flooding (20 MPa, 100 °C)

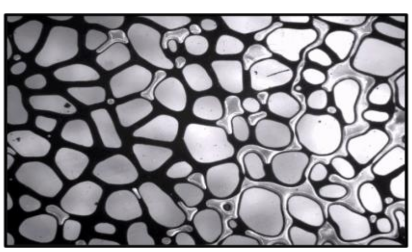

Fig.19. After adding oil-soluble CO_2 synergist, the remaining oil distribution after CO_2 flooding (20 MPa, 100 °C)

Dissolution viscosity reduction, dissolved gas flooding, expansion and wave propagation are the main mechanisms for super heavy oil CO_2 to produce residual oil.

After supercritical CO_2 injection, the sweep efficiency is low, and it is easy to form columnar, cluster and other types of residual oil.

During the soaking process, CO_2 is obviously dissolved in oil.

In the process of depletion mining, the gas phase forms a large number of small bubbles and expands rapidly, and the sweep efficiency is improved.

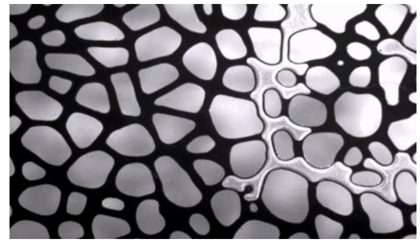

Fig.20. CO_2 injection (20 MPa, 100 °C)

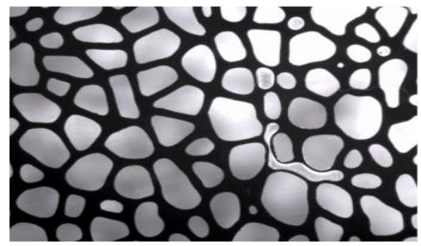

Fig.21. CO_2 soaking (20 MPa, 100 °C)

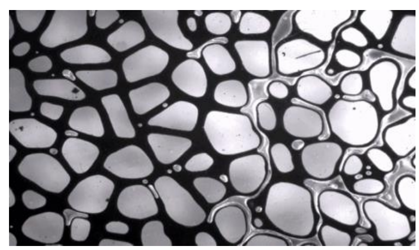

Fig.22. CO_2 depletion mining (100 °C)

4. CONCLUSIONS

Supercritical CO_2 can improve the physical properties of ultra-deep heavy oil, expand and increase energy, reduce the density and viscosity of crude oil, improve the rheology of crude oil, and improve the quality of crude oil.

Supercritical CO_2 can reduce the viscosity of heavy oil in porous media and extract heavy oil components, but the rate of action is longer than that of light oil/ordinary heavy oil.

The oil displacement mechanism of supercritical CO_2+synergist in the displacement process is emulsification dissolution viscosity reduction and formation of foam oil to expand sweep efficiency.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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