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Exploration and application of CO_2 huff-and-puff technology to individual wells and blocks with hard-to-recover reserves

Kuifeng Dong[1], Zezong Zhao[1], Xiaoqi Li[1], Guinian Li[1], Jiaqi Jiang[1], Guangsheng Zhang[1], Changyun Liu[1], Shede Dai [1], Meng Wang [1], Sheng Zhang [2*]

1 Affiliation of author A

2 Affiliation of author B
(*Corresponding Author: Email:2020005110@zut.edu.cn)

ABSTRACT

It is imperative to acknowledge the significance of the existing single well ,single-block reservoirs within the Wenliu Oilfield, as their inherent limitations hinder the establishment of a comprehensive drilling network, the extent of their productivity, and the efficient development of their potential. The imminent necessity to enhance oil recovery (EOR) rate of "three-low" (low permeability, low productivity, low efficiency) reservoirs is underscored by the prevailing challenges. The implementation of CO_2 huff-and-puff (CO_2 HnP)in conjunction with wells possessing a certain degree of storage capacity can yield a substantial augmentation in the recovery rate of oil. This approach is characterized by its cost-effectiveness and expeditious outcomes. Through the utilization of numerical simulation techniques, the optimization of the slug injection methods and the design of injection parameters can be achieved. This facilitates the reduction of operational periods and the attainment of enhanced recovery rates. In order to optimize the ground injection process and tubular designs, as well as the supporting anti-corrosion process, it is essential to improve CO_2 HnP monitoring technology in order to guide the field application. Furthermore, the application of quantitative characterization technology of CO_2 displacement leading edge is required to guide the optimization of the implementation of the plan. Finally, the formation of the CO_2 HnP process should be facilitated. From 2022 to 2025, 3 well-times of CO_2 HnP were conducted in single well and individual block difficult-to-produce reserves, with cumulative injection of 3655.4 t CO_2 and cumulative water injection of 8350 m^3 by water injection slug. Up to now, the cumulative oil increment is 1462 t and the oil exchange ratio is 0.4 t/t, a excellent level of CO_2 utilization is achieved.

Keywords: single wells and individual blocks； enhanced oil recovery (EOR); optimization design; CO_2 huff-and-puff technology

1. INTRODUCTION

The global emphasis on mitigating greenhouse gas-driven climate change has prompted China to establish its "dual carbon" goals (carbon peaking and carbon neutrality). Zhongyuan Oilfield has pioneered CO_2 utilization through CCUS-EOR (Carbon Capture, Utilization and Storage-Enhanced Oil Recovery) technology, transforming harmful atmospheric CO_2 into underground assets while boosting oil recovery and reducing carbon emissions.[1-3]As a fault-block reservoir with substantial yet challenging-to-develop geological reserves per single-well block, Wenliu Oilfield required innovative approaches. Extensive research confirms that CO_2 demonstrates strong solubility in crude oil, triggering a cascade of physicochemical effects,such as volume expansion,viscosity reduction,interfacial tension reduction,enhanced fluid mobility through increased reservoir elastic energy.These mechanisms synergistically liberate water-bound residual oil from capillary forces,mobilizing trapped oil from small pores (5-50μm) into producible phases,thereby improving macroscopic sweep efficiency and microscopic displacement efficiency.The resultant 5-20% increase in ultimate recovery factor has made CO_2 injection a widely adopted enhanced oil recovery (EOR) technology, particularly effective in low-permeability (<50mD) and high-viscosity (>50mPa·s) reservoirs. Field data shows CO_2-EOR can extend field life by 10-15 years while sequestering 0.3-0.5 tons of CO_2 per ton of incremental oil produced.Since commencing CO_2 huff-and-puff field trials in 1998, Zhongyuan Oilfield has conducted 13 cyclic injection operations by 2021,

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delivering 1,093t of incremental oil through 2,867t CO_2 injection (0.38t/t replacement ratio). With a 54% technical efficacy rate, this technology proves particularly effective for developing compartmentalized marginal reserves with limited well-pattern connectivity, indicating substantial scalability potential.

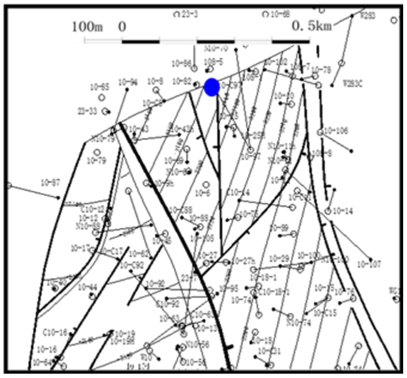


Fig. 1. Structural map of well location

In the Dongpu mature field, the elastic drive systems are mainly distributed in scattered blocks[4]developed through progressive exploration, retaining 13.77×10^6 t of technically marginal reserves with sub-10% recovery factors. Particularly in the Wenliu viscous oil zone where the recovery efficiency remains critically low, CO_2 huff-and-puff emerges as the optimal EOR strategy for reserve activation.[5]Located in the structurally complex Wenliu anticlinal belt (Central Uplift Zone, Dongpu Depression), this 122.69 km^2 oilfield cluster (Wenzhong-Wendong-Wenan) produces from multiple stacked pay zones within the lacustrine deltaic Shahejie Formation (Paleogene), predominantly from Fluvial-dominated delta front sands (Lower Es_2),Deep-water turbidites (Upper Es_3),Sublacustrine fan systems (Middle Es_3).For example, Well Wen 10-C97 is located in the northern sector of Block Wen 10 East, representing a single-well, single-block development unit currently produced under natural depletion drive. Key reservoir characteristics include 21,000 metric tons original oil in place (OOIP),9.5% recovery,low reservoir energy (exhibiting both low pressure and low productivity).As of June 17,2022, the pressure in the middle of the reservoir was 17.17 MPa, and the converted formation pressure coefficient was 0.65, which met all screening criteria for CO_2 huff-and-puff stimulation and is classified as a priority candidate for cyclic CO_2 injection to achieve.

2. CO_2 HNP PROCESS

2.1 *CO_2 HnP Stimulation Stimulation Mechanisms*

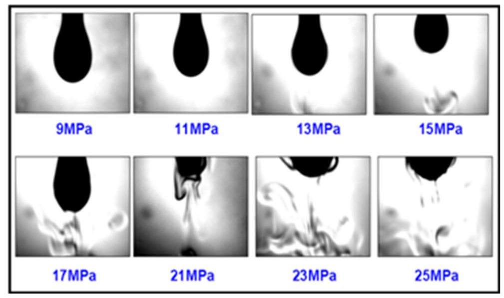


Fig. 2. Phase behavior diagram of CO2-Crude Oil

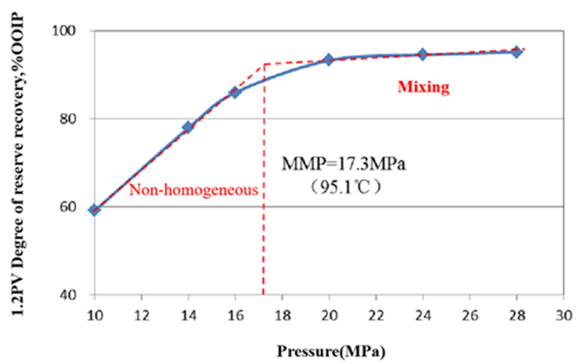


Fig. 3. Displacement efficiency vs. Pressure relationship curve

The CO_2 HnP process involves multiple interacting mechanisms, with their relative contributions varying across reservoir types. Laboratory experiments and field trials demonstrate that the dominant mechanisms are as follows.[6-10]When CO_2 achieves miscibility (or near-miscibility) with crude oil, interfacial tension (IFT) approaches zero, significantly improving displacement efficiency.[11]Higher miscibility degrees yield better

Table 1 Comparative analysis of crude oil properties before and after CO_2 Huff-and-Puff stimulation

Well	Density/ ρ50	Viscosity(mPa.s) 50℃	Colloid(%)	Annotation
X1	0.9601	3023	38.54	Initial
X2	0.9592	2243	34.39	Post-Stimulation
差值/降幅	-0.0009	-780（25.8%）	-4.15	
X3	0.9489	1260.5	25.49	Initial
X4	0.9483	978	24.69	Post-Stimulation
差值/降幅	-0.0006	-282.5（22.4%）	-0.8	

recovery. CO_2's high compressibility rapidly restores reservoir energy. Multi-contact experiments reveal that at 35% CO_2 mole fraction, the solution gas-oil ratio (GOR) increases from 33.8 to 105 m^3/m^3, with 11% oil volume expansion. In heavy oil reservoirs (e.g., 150–500 cP), a 41% CO_2 mole fraction reduces viscosity by up to 84%. Post-stimulation viscosity declines exceed 20%, enhancing flowability. Initial CO_2 injection causes slight permeability reduction due to fine migration and inorganic scaling (e.g., calcite precipitation).[12] Prolonged CO_2 exposure dissolves carbonate minerals, increasing porosity by 9.24% and restoring permeability.[13]Miscibility eliminates oil-gas IFT,minimizing capillary trapping. Higher Injection pressures promote miscibility, elevating sweep efficiency.

2.2 Numerical Simulation of CO_2 HnP Process

This approach integrates reservoir characteristics, fluid properties, and production history to construct a

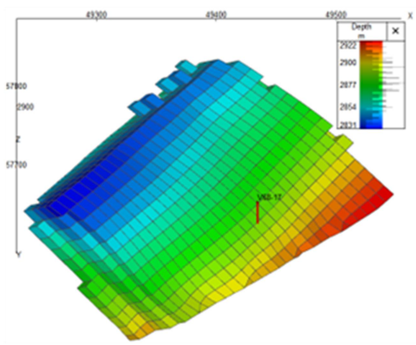


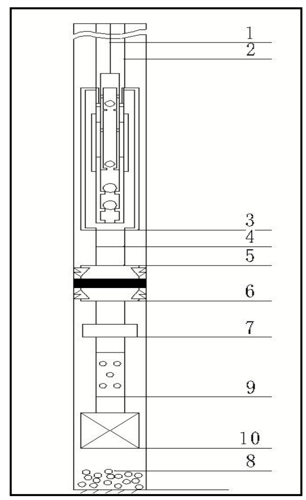
Fig. 4. Development of a Simulation-Ready Reservoir Model

CO_2 HnP reservoir model.[14-15]Through numerical simulation, it evaluates the effects of varying stimulation parameters (e.g., injection volume, soaking time, cycle count) to guide the design and optimization of CO_2 HnP stimulation programs.

This study employs numerical simulation-based optimization to determine the optimal injection parameters, including the CO_2 injection volume, injection rate， water-alternating-gas (WAG) slug size.[16-19]The objective is to maximize the oil-CO_2 exchange ratio (target >0.4 t/t) while considering reservoir constraints (e.g., fracture pressure, fluid compatibility).

2.3 Enhancement of Surface Injection Facilities for CO_2 HnP Operations

Liquid CO_2 is transported via tanker trucks and injected through a skid-mounted short-flow boosting system at the wellhead. High-pressure injection lines are surface-laid and anchored, enabling rapid deployment and low operational costs. Based on well type, the retrievable packer string, pump-compatible string and injection-production integrated string for CO_2 HnP injection can be adopted. The retrievable packer string is for wells with compromised casing integrity in upper sections. The pump-compatible string is for producing wells with existing downhole pumps. The injection-production integrated string is designed for multi-cycle CO_2 HnP operations via tubing, whose tubing string configuration is tubing + gas-resistant injection-production pump + insert tube + re-insertable packer +soluble cathodic protector + ball seat + sand screen + plug. The gas-resistant injection-production pump ensures independent pathways for segregated injection and production channels. The Gas-Liquid separation is enhanced pump efficiency by reducing barrel pressure during production. Simultaneous production is capable of co-producing gas and liquid phases.



1—Sucker Rod；2—Tubing；3—Gas-Resistant Injection-Production Pump；4—Slip Joint；5—Insert Tube；6—Re-Insertable Packer；7—Cathodic Protector；8—Solid Corrosion Inhibitor；9—Sand Screen；10—Plug；

Fig. 5. Schematic diagram of injection-production integrated tubing string

Prior to gas injection, a 2,000 ppm CO_2-resistant oilfield corrosion inhibitor solution is circulated for one wellbore volume via reverse flushing to apply pre-filming anti-corrosion treatment on the following components. During the well soaking period (typically 10-day intervals), batch injection of corrosion inhibitor shall be performed based on annular fluid level monitoring, with dosage adjusted to maintain adequate film protection. The anti-corrosion measures during production shall comply with Q/SH 1025 0976-2015 (Technical Requirements for Corrosion Inhibitor Dosing in Oilfield Systems). The CO_2-resistant corrosion inhibitor dosage shall be designed based on the geologically predicted daily liquid production rate.

Table 2 Corrosion protection process during production phase

CO_2 concentration	Dosage concentration of CO_2-resistant liquid corrosion inhibitor	Safety factor	Injection rate	Annotation
＜10%	α × 400mg/L	1-3	Equipped with an intelligent dosing system for automated daily injection at a controlled rate of 2 – 5 L/h.	The CO_2 -resistant liquid corrosion inhibitor and oxygen-scavenged water shall be mixed at a ratio of 1:1 to 1:3 (inhibitor:water) before injection, with the dosage calculated based on the volume of the CO_2 -resistant inhibitor alone.
10%～50%	α × 400mg/L～α × 1200mg/L			
＞50%	α × 1200mg/L～α × 2000mg/L			

2.4 Enhancement of CO_2 flooding monitoring technologies

The ultra-long activation period tracer was innovatively introduced, and the ultrasonic atomizers and array gamma detector were used to realize the homogeneous mixing with supercritical CO_2 and precise identification. A tracer flow injection profile testing technology is developed, which can identify the flow rate of 10 t/d under the condition of 150 °C and 70 MPa, and solve the profile monitoring problem of high pressure, low permeability and small displacement gas injection wells. The half-life of the active tracer is 153 seconds (7.13 seconds for the oxygen activation instrument) , and the effective detection time is increased by 20.5 times. The quantitative measurement accuracy of small layer suction is 0.5 t/d by the combination of continuous and point measurement process. The minimum detectable flow rate is 0.5 m/(3 × 2.55) min = 0.065 m/min, the daily flow distance is 0.065 * 1440 = 94.12 m, the minimum casing flow rate is 1.13 t/d, the minimum annular flow rate is 0.85 t/d, and the minimum flow rate is 0.31 t/d in the tubing.

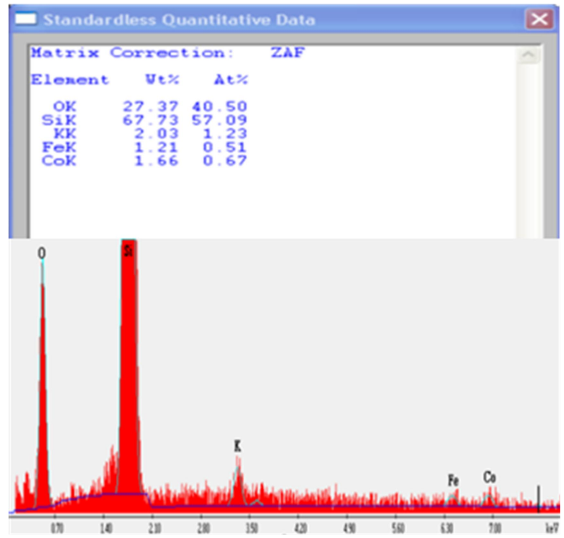


Fig. 6. Laboratory gamma intensity testing of tracer stock solution

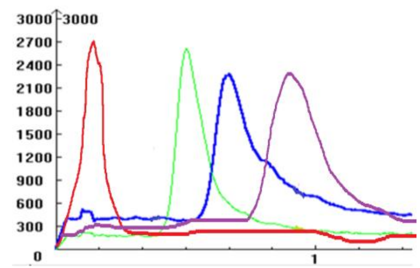


Fig. 7. Detection signal

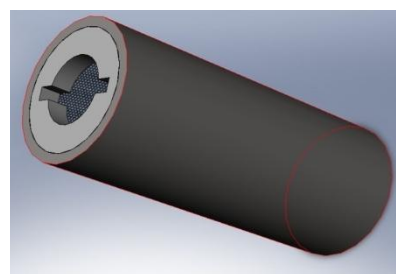


Fig. 8. Tracer stock solution activation system

2.5 Field application guidance for CO_2 flooding monitoring technologies

The activated tracer CO_2 injection profile testing technique can be used to determine the casing leakage location. Under the condition of activated tracer flow test and CO_2 injection rate of 10 t/d, the casing leakage can be accurately identified, which provides technical basis for the next safe disposal.

2.6 Mixed-phase pressure

Pressure drop test was applied to analyze the leading edge of gas injection during the casing of Wen 10-C97 well. The minimum mixed-phase pressure was 20.03 MPa, and the mixed-phase throughput was reached by reducing the CO_2 dosage through water injection energy augmentation.[20]

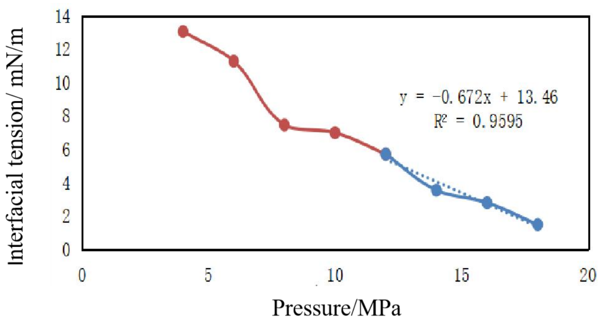


Fig. 9. Wen10-C97 CO_2-crude oil interfacial tension

2.7 Explore the formation of carbon dioxide throughput well selection principles and parameter design to form a supporting technology

(1) Key well selection criteria for CO_2 HnP in Zhongyuan Oilfield were identified

According to the industry standard, based on the reference to the domestic oilfield counterparts' well selection principles, combined with the local oilfield, we formulate the CO_2 HnP well selection criteria for Zhongyuan Oilfield(Table 3).

parameter, the fuzzy judgment matrix is established and consistent, and the weight vector of each factor is determined, and the variable weight matrix is obtained. Finally, the final evaluation membership degree result is obtained. The higher the degree of membership as a priority CO_2 HnP wells (Table 4).

(2) Enhancement of CO_2 HnP supporting technologies

In order to effectively replenish the energy of the severely deficient formation and optimize the CO_2 throughput injection method, the water section plug energy-enhancing assisted CO_2 throughput process was implemented in this well, specifically using the injection of water section plugs to enhance the formation pressure to reach the degree of near-mixed-phase.

(3) Dynamic monitoring & data acquisition

A sampling point is established at the wellhead, and the associated gas of the output fluid is regularly taken for component analysis and the CO_2 content is calculated for surface corrosion monitoring. During the pumping production stage, the pumping pipe is equipped with corrosion monitoring device, which is divided into upper, middle and lower parts to monitor the corrosion condition of the wellbore. In the process of pumping production, the corrosion inhibitor dosing concentration is dynamically optimized according to the output CO_2 content and iron ion concentration.

Table 3 CO_2 HnP well selection criteria for Zhongyuan Oilfield

Factor	Economic Screening Criteria	Technical Screening Criteria (for Optimal Performance)
Miscibility degree	Stratigraphic crude oil and CO2 are prone to miscible phases	⩾MMP(1-1.3 times)
Permeability	10~100mD	10~100mD
Stratigraphic cyclicity	Normal Gradin; Heterolithic Rhythm	Recommendation for Upward-Coarsening Sequences
Optimal timing for HnP Operations	Pressure coefficient > 0.5	Pressure coefficient >0.7
Artificial Fracture	Artificial fracturing is mandatory for tight oil/gas reservoirs.	Optimized fracture design outperforms maximized scale.

The evaluation system of CO_2 HnP is established, and the fuzzy analytic hierarchy process is used to guide the implementation sequence of CO_2 HnP Wells. To determine the well selection parameters of CO2 HnP wells[21](reservoir thickness, permeability, miscibility, oil saturation, crude oil viscosity, recovery degree, wellbore integrity, surface engineering support, etc.) , according to the membership degree of each evaluation

Take complete and accurate production data of oil, gas and water production data during normal production in the 6 months before construction, dynamometer card, casing pressure and dynamic liquid level data, and measure formation static pressure before gas injection. Conduct a routine analysis of oil, gas and water before CO_2 HnP construction. Take full and accurate data of injection volume, pump pressure,

Table 4 Key design parameters for CO_2 HnP operations

Injection volume	Injection rate	Soaking time	Flowback Procedure
①SY/T6487 Recommended Practices for Liquid CO_2 Huff-and-Puff Stimulation, The standard specifies that injection intensity shall be customized based on reservoir types ②Volumetric Method ③Minimum Miscibility Pressure (MMP) Calculation Approaches ④Numerical Simulation-Based Optimization Method	SY/T 6487 Recommended Practices for Liquid CO_2 Huff-and-Puff Stimulation, Maximize injection ratewhile maintaining bottomhole pressure below fracture pressure	①SY/T 6487 Recommended Practices for Liquid CO_2 Huff-and-Puff Stimulation, Terminate soaking phase upon achieving stable wellhead pressure for 7 consecutive days②Real-Time adjustment of soaking duration based on pressure decline trends in Zhongyuan Oilfield field practice ③Wellhead Pressure Decline <0.5 MPa Over 48 Hours	①Zhongyuan Oilfield implements 2 − 5 mm choke for controlled flowback, with 2 mm chokes mandatory for sand-prone wells ②Field flowback operations utilize 2 − 8 mm Chokes

oil pressure, casing pressure, injection temperature, injection rate during injection and wellhead oil pressure and casing pressure during well soak. Take the complete and accurate production data of oil, gas and water, oil and gas composition, crude oil composition and salinity of produced water from the recovery of production of huff and puff wells until the end of CO_2 HnP effect. Take the corrosion rate monitoring data of the whole huff and puff well (iron ion concentration, monitored once a week) to analyze the anti-corrosion effect. Pay attention to the production performance of adjacent wells in the injection and soak stages. If gas channeling is found, the gas channeling well shall be shut in in time.

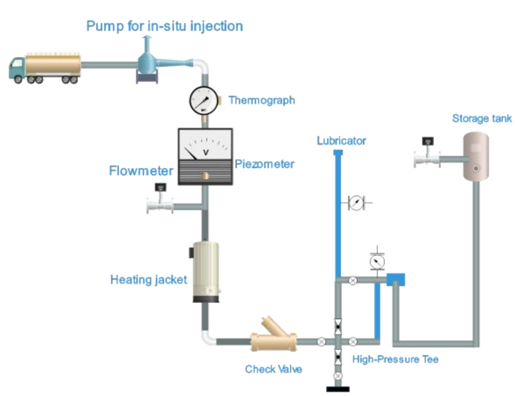


Fig. 10. CO_2 HnP injection procedure

3. SUMMARY OF FIELD EXECUTION PERFORMANCE

The CO_2 work of Zhongyuan Oilfield began in 2007. So far, 47 well groups in 19 blocks have been implemented on site, covering 23.2728 million tons of geological reserves, with a cumulative gas injection of 833600 tons and a stage oil change rate of 0.22t/t. Since 2022, CO_2 HnP has been used for medium permeability thin oil to increase energy and improve mobility ratio. Through miscible phase to improve oil displacement efficiency, increase energy and reduce viscosity to improve mobility ratio and reservoir permeability, water injection assisted CO_2 miscible huff and puff has been implemented for 3 wells, with 3655.4t CO_2 injected and 8350m3 water injected in water slug. Up to now, 1462t oil has been added and the oil change rate is 0.38t/t, achieving good CO_2 HnP effect. It provides a good technical basis for the next step to expand the transformation of scientific and technological achievements.

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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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