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Research and Application of Minimum Miscibility Pressure in Enhanced Oil Recovery

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Abstract

With the increasing depletion of conventional oil and gas resources, enhanced oil recovery technology has become the key to maintaining high and stable production in oil fields. Among various EOR technologies, gas displacement, especially mixed-phase displacement, is regarded as one of the most effective methods due to its ability to significantly reduce the residual oil saturation of oil reservoirs. The minimum mixed-phase pressure is a key parameter for achieving gas-flooding mixed-phase in the oil and gas extraction process, directly affecting the efficiency of enhanced oil recovery. This paper reviews the definition, influencing factors, experimental determination methods and theoretical models of the minimum mixed-phase pressure, and discusses its application in oilfield development. Research shows that the accurate determination of the minimum mixed-phase pressure can optimize the gas injection process, reduce development costs and enhance crude oil recovery rate.

Keywords

Minimum Mixed-phase Pressure; Enhanced Oil Recovery; Mixed-Phase Flooding; Carbon Dioxide Flooding; Fine Tube Displacement.

1. Introduction

After secondary oil recovery (such as water flooding) is completed, approximately 50% to 70% of the original geological reserves still remain in the reservoir pores in the form of residual oil. The goal of enhanced oil recovery technology is precisely to utilize this part of the hard-to-extract resources. Mixed-phase flooding involves injecting gases (such as CO_2, hydrocarbon gases, nitrogen, etc.) to mix with formation crude oil under specific conditions, forming a single phase state. This reduces the interfacial tension to nearly zero, significantly enhancing the micro-displacement efficiency. Theoretically, it can increase the recovery rate to over 90%. The minimum pressure condition for achieving mixed phase, that is, the minimum mixed phase pressure, is the economic and technical critical point that determines the success or failure of mixed phase drive. Its precise measurement is of vital importance to the scheme design. [1-3]

2. Organization of the Text

2.1. The Concept and Mechanism of the Minimum Mixed-Phase Pressure

The minimum mixing pressure is defined as the lowest pressure required for the injected gas to achieve dynamic mixing with crude oil through multiple contacts at the reservoir temperature. Its mechanisms mainly fall into two categories:

1. Vaporization mixing: When poor gas (such as N_2, CH_4) is injected, the gas comes into multiple contacts and extracts (vaporizes) the intermediate components (C_2-C_6) in the crude oil, enriching the front end of the gas and ultimately achieving phase mixing with the crude oil.

2. Condensation phase mixing: When rich gas (hydrocarbon gas rich in C_2-C_6) is injected, the intermediate components in the gas condense into the crude oil, causing changes in the crude

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oil composition (lightening), and ultimately achieving phase mixing with the subsequent injected gas.

CO_2 flooding, on the other hand, is usually a comprehensive mechanism that involves both vaporization and condensation processes.

2.2. The Method for Determining the Minimum Mixed-Phase Pressure

Accurately determining the minimum mixed-phase pressure is a prerequisite for the successful implementation of mixed-phase drive, and its main methods can be classified into three categories:

1) Experimental determination method

The fine tube test: regarded as the "gold standard" for determining the minimum mixed-phase pressure. Crude oil is saturated in a long tube filled with fine sand, and gas is injected at a constant rate under different pressures to calculate the recovery rate. The pressure corresponding to a sudden increase in recovery rate (usually >90%) is the minimum mixed-phase pressure. This method is reliable in its results, but it is time-consuming, labor-intensive and costly.

Bubble rise meter experiment: Quickly estimate the minimum mixing pressure by observing the morphological changes of bubbles in crude oil. The pressure corresponding to the deformation, vibration and dissolution of the bubble is the minimum mixed-phase pressure. This method is fast and low-cost, but it is highly subjective.

Interfacial tension disappearance method: The interfacial tension between oil and gas at different pressures is measured by the suspension drop method. The pressure extrapolated to zero interfacial tension is the minimum mixed-phase pressure. This method is intuitive and can be applied to non-equilibrium systems.

2) Empirical formula association method:

Based on a large amount of experimental data, empirical formulas between the minimum mixed-phase pressure and crude oil components, injection gas composition and reservoir temperature were established (such as Cronquist, Yelling & Metcalfe formulas, etc.). This method is fast and convenient, but its accuracy is limited and it is suitable for screening and preliminary assessment.

3) Numerical simulation calculation method:

The PVT characteristics of crude oil and injected gas are fitted by using the equation of state, and the recovery rates at different pressures are calculated through a one-dimensional component simulator (such as a fine tube simulation), thereby determining the minimum mixed-phase pressure. This method is highly flexible and can study the influence of multiple factors, but its accuracy is highly dependent on the precision of EOS tuning. [4-5]

2.3. Application and Challenges of Minimum Mixed-Phase Pressure in EOR

Project design and optimization: The minimum mixed-phase pressure is the core basis for determining the injection pressure, well pattern deployment and completion plan. The injection pressure must be slightly higher than the MMP to ensure miscibility, but at the same time it should be lower than the formation fracture pressure.

Injection gas screening: Compare the MMP of different gases CO_2, N_2, flue gas, hydrocarbon gas) with that of the target crude oil, and select the injection medium that is technically feasible and economically optimal. CO_2 is currently the most widely used mixed-phase displacement gas due to its relatively low minimum mixed-phase pressure and environmental benefits (storage).

Economic assessment: The minimum mixed-phase pressure directly affects the energy consumption cost of compressed gas and is a key parameter for evaluating the economic feasibility of EOR projects.

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Challenge: Reservoir heterogeneity: Changes in the permeability of the actual reservoir can cause injection gas to flow through, resulting in local pressure being lower than MMP, thereby disrupting the mixed phase and affecting the displacement effect.

The complexity of crude oil components: The presence of heavy components such as asphaltenes may affect phase behavior, making the prediction and experimental determination of the minimum mixing pressure more difficult.

Economic pressure window: For oil reservoirs with high minimum mixed-phase pressure, the required injection pressure may approach or exceed the formation fracture pressure, which limits the application of mixed-phase flooding.

2.4. Minimum Mixed-Phase Pressure Fine Tube Experiment

Experimental setup: Minimum mixed-phase pressure fine tube experimental setup

Experimental materials: Crude oil, shale oil cores;

Experimental method: It was carried out in accordance with the industry standard "Determination Method of Minimum Mixed Phase Pressure by Fine Tube Test" (SYT 6573-2003). The fine tube method was used to conduct the minimum mixed phase pressure test on 20 crude oil samples from 4 blocks in the Longdong area.

Preparation of the instrument

The specific parameters of the fine pipes in the design are shown in Table 1, and the connection diagram of the device is shown in Figure 1.

Table 1. Basic Parameters of the Thin Tube

Main parameters	Parameter value
Maximum temperature	150℃
Maximum pressure	70MPa
Length of thin pipe	12m
Inner diameter	5mm
Filler (quartz sand)	160-200 mesh
Total volume of the fine tube	235.5cm^3
Porosity	37.54%
Penetration rate	1.2mD

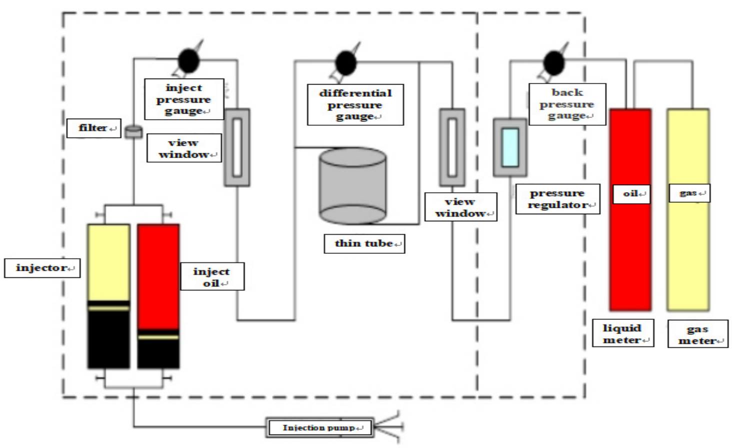

Figure 1. Diagram of the fine tube experimental setup

Experimental procedures

1) Connection pipe experimental device.

2) Before each experiment, the fine tube should be thoroughly cleaned with petroleum ether. The cleaning is completed when the color and composition of the petroleum ether injected from the inlet of the fine tube are the same as those flowing out from the outlet. Generally speaking, the fine tube should be cleaned at least three times.

3) After cleaning is completed, blow the clean fine tubes dry with nitrogen and then dry them in an oven for more than 6 hours at the same time.

4) After the fine tubes are dried, the porosity and permeability are measured again and the pore volume PV is calculated.

5) Saturated crude oil is ready for use under formation temperature and selected displacement pressure conditions.

6) Add an appropriate amount of ground degassed oil to the sample preparation cylinder, seal it and heat it to the formation temperature, stabilizing for about 4 hours.

7) After the temperature stabilizes, calculate the amount of gas sample used based on the weight of the oil sample loaded and the original ratio of dissolved gasoline.

8) Inject the required gas sample into the sample preparation cylinder, pressurize it to the formation pressure, maintain the formation temperature and pressure, stir thoroughly to make it a single phase, and stabilize it for more than 4 hours.

9) Determine the saturation pressure and gas-oil ratio of the blended crude oil.

If the saturated pressure differs significantly from the actual saturated pressure of the formation oil, adjust the dissolved gas volume of the oil in the sample preparation cylinder until the measured saturated pressure and dissolved gas-oil ratio are the same as or close to those of the original formation oil.

10)After the experimental system is installed, the vacuum pump drawer is set to a vacuum state. Then, the temperature of the constant temperature control box is adjusted to the formation temperature and the pressure to the formation pressure. At the same time, crude oil is saturated in the fine tube. Then, the intermediate container is filled with displacement gas samples and maintained in balance.

11) Use the back pressure regulator to control the back pressure and adjust it to the pressure value required for the experiment.

12) After the gas sample is displaced at a constant speed to 1.2 times the pore volume using an injection pump, the entire displacement process is completed.

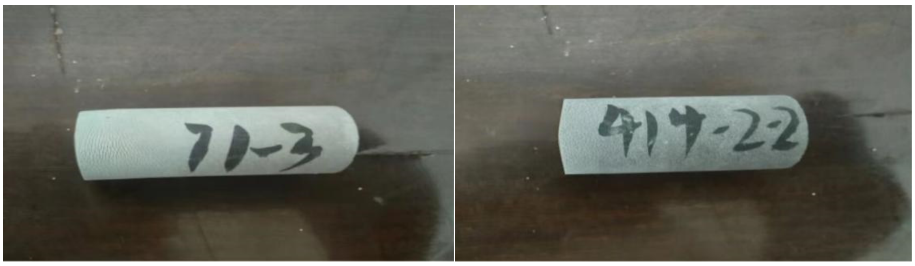

Figure 2. Core sample diagram

13) The extracted oil samples are measured once at regular intervals using a liquid collector, and the extracted gas volume is measured by a gas meter.

14) Repeat the above steps by selecting different pressures. Generally, six pressure points are chosen, with three above the mixed-phase pressure and three below the mixed-phase pressure.

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15) Calculate the recovery rate and draw the relationship curve between pressure and recovery rate. The pressure corresponding to the inflection point of the curve is the minimum mixing pressure. Obtain the theoretical predicted minimum mixed-phase pressure.

Experimental steps for minimum mixed-phase pressure displacement

1)After the experimental system is installed, the vacuum pump drawer is set to a vacuum state. Then, the temperature of the constant temperature control box is adjusted to the formation temperature and the pressure to the formation pressure. At the same time, crude oil is saturated in the fine tube. Then, the intermediate container is filled with displacement gas samples and maintained in balance. [6-8]

2) Use the back pressure regulator to control the back pressure and adjust it to the pressure value required for the experiment.

3) After using an injection pump to displace the gas sample at a constant speed to 1.2 times the pore volume, the entire displacement process is completed.

4) For the oil samples collected, the process steps of the displacement experiment should be carried out at regular intervals. Draw a curve of the relationship between pressure and recovery rate. The pressure corresponding to the inflection point of the curve is the minimum mixed-phase pressure.[9-12]

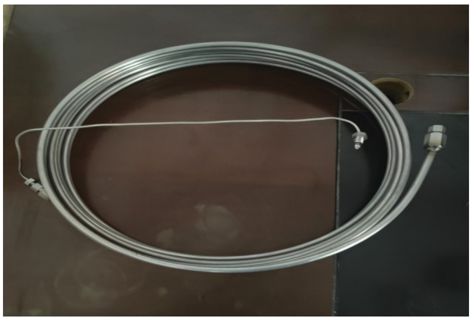

Figure 3. Physical picture of the thin tube

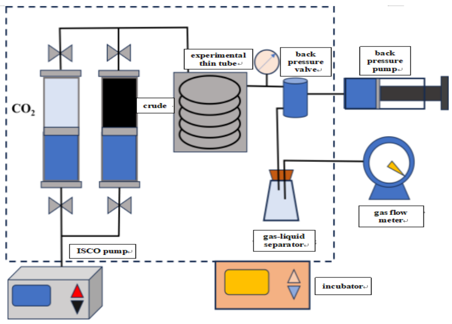

Figure 4. Diagram of the displacement experiment setup

Li 434 minimum miscibility pressure is determined

Table 2. Under the different displacement pressure injection recovery when 1.2 PV

Test pressure (Mpa)	Recovery rate (%)
9	61.72
11	75.83
13	84.64
15	92.48
17	94.66
19	95.39

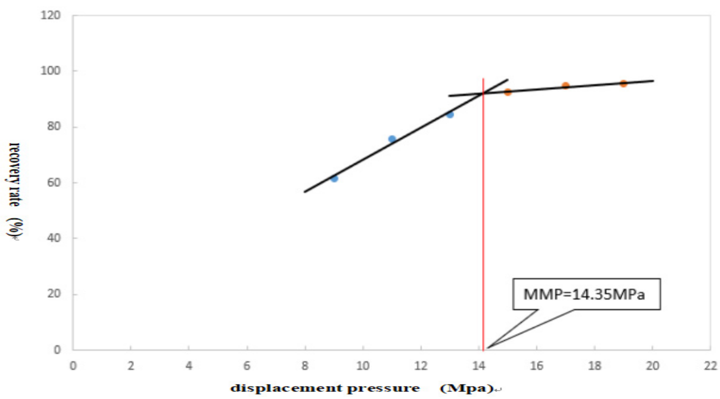

Figure 5. Curve of CO_2 displacement recovery and displacement pressure

It can be obtained from the figure that the minimum miscibility pressure of carbon dioxide flooding is 14.35MPa at the temperature of 58.9℃ for the crude oil sample of formation Li 434.

Zhu 16 minimum miscibility pressure is determined

Table 3. Under the different displacement pressure injection recovery when 1.2 PV

Test pressure (Mpa)	Recovery rate (%)
9	60.61
11	73.71
13	84.57
15	90.34
17	91.51
19	92.23

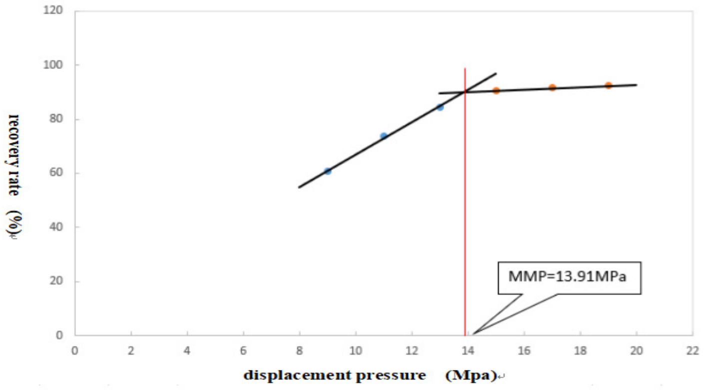

Figure 6. Curve of CO_2 displacement recovery and displacement pressure

It can be obtained from the figure that the minimum miscibility pressure of carbon dioxide flooding is 13.91MPa at the temperature of 56.7℃ for the crude oil sample of Zhu16 formation.

Ban 69 minimum miscibility pressure is determined

Table 4. Under the different displacement pressure injection recovery when 1.2 PV

Test pressure (Mpa)	Recovery rate (%)
8	62.67
10	74.16
12	83.05
14	92.15
16	93.27
18	93.62

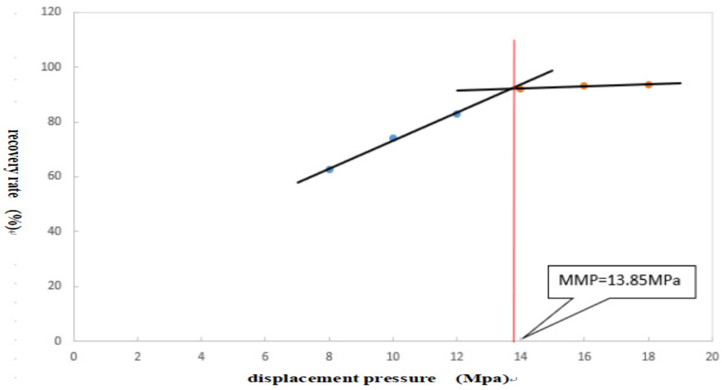

Figure 7. Curve of CO_2 displacement recovery and displacement pressure

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It can be seen from the figure that the minimum miscible pressure of carbon dioxide flooding is 13.85MPa at the temperature of 56.3°C for the crude oil sample from the formation of Ban69.

Ban 64 minimum miscibility pressure is determined

Table 5. Under the different displacement pressure injection recovery when 1.2 PV

Test pressure (Mpa)	Recovery rate (%)
8	61.87
10	71.96
12	82.15
14	90.5
16	91.72
18	92.27

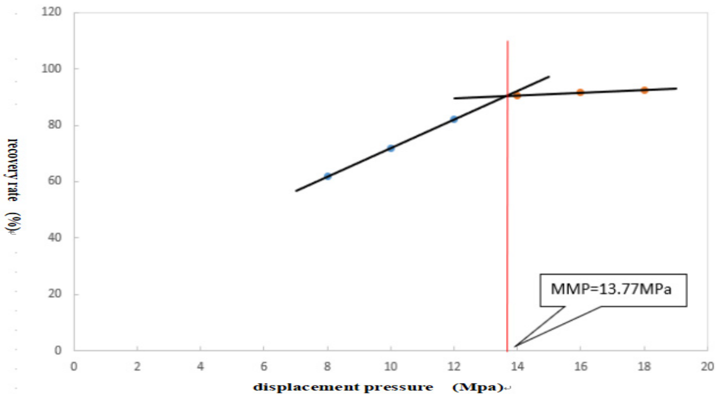

Figure 8. Curve of CO_2 displacement recovery and displacement pressure

It can be obtained from the figure that the minimum miscibility pressure of carbon dioxide flooding is 13.77MPa at a temperature of 56.3°C for the crude oil sample of Ban64 formation.

Experimental Results and Analysis

Affected by the differences in reservoir temperature and fluid composition, the mixing capacity of shale oil and CO_2 in different areas of eastern Gansu shows differences. The minimum mixing pressure from high to low is Qingchengnan (14.313MPa), Huanxian (14.037MPa), Huachi (13.973MPa), and Heshui (12.957MPa) in sequence. So the CO2 in the four blocks can be completely mixed. Among the four blocks, the extent to which CO2 mixed-phase displacement enhances recovery is much greater than that of non-mixed-phase displacement, and the recovery degree is all above 92%. [13-15]

3. Organization of the Text

The minimum mixed-phase pressure (MMP) is a cornerstone parameter in the mixed-phase drive technology for enhanced oil recovery. Through the comprehensive application of various methods such as experiments, experience and numerical simulation, MMP can be determined relatively accurately, providing scientific guidance for the successful implementation of EOR projects.

In the future, the research and application of MMP will present the following trends:

1. Intelligence and big Data: By integrating machine learning algorithms and leveraging massive experiments and oilfield data, a more accurate and universal MMP intelligent prediction model is established.

2. Low-cost technology: Develop new MMP determination technologies that are faster and more economical to reduce the research costs in the early stage of the project.

3. Non-pure CO_2 displacement: This study examines the mixed-phase behavior of non-pure CO_2 gases such as industrial waste gas and flue gas with crude oil, aiming to enhance recovery while achieving carbon capture, utilization and storage (CCUS), offering both economic and environmental benefits.

4. Research on Complex Systems: Deepen the understanding of the mixed-phase processes in complex oil reservoirs such as asphaltene and fractured reservoirs, and expand the application boundaries of mixed-phase flooding.

In conclusion, the continuous in-depth research and precise application of MMP will continue to drive the development of mixed-phase drive technology and make significant contributions to the sustainable development and energy security of the global petroleum industry.

References

[1] Li K ,Li T ,Wang X , et al.Models for Predicting the Minimum Miscibility Pressure (MMP) of CO_2-Oil in Ultra-Deep Oil Reservoirs Based on Machine Learning[J].Energy Engineering,2025,122(6):2215-2238.

[2] Dong Z ,Hou T ,Li W , et al.Effect of surfactants C12PO6 and SW320 on oil/CO_2 minimum miscibility pressure of unconventional liquid reservoirs - molecular dynamics simulation study[J].Geoenergy Science and Engineering,2025,251213863-213863.

[3] Zang H ,Dong Z ,Zhang Z , et al.Thermodynamic calculation studies on oil composition and water presence effect on the minimum miscibility pressure of the CO_2/two-components oil system[J]. Chemical Thermodynamics and Thermal Analysis,2025,18100183-100183.

[4] Hao H ,Xian B ,Peng M , et al.Study of Different Gas Floodings on Minimum Miscibility Pressure and Oil Recovery in a Low-Permeability Reservoir with Medium Viscous Oil.[J].ACS omega, 2025, 10 (9): 9426-9440.

[5] Song Y ,Song Z ,Mo Y , et al.Determination of minimum miscibility and near-miscibility pressures for CO_2-oil mixtures in shale reservoirs[J].Fuel,2025,388134531-134531.

[6] Liu F ,Zhang S ,Zhang J , et al.Molecular Dynamics Study on the Nature of near Miscibility and the Role of Minimum Miscibility Pressure Reducer[J].Processes,2025,13(2):535-535.

[7] Yang K ,Yang S ,Hu J , et al.Research on Component Variation and Factors Affecting Minimum Miscible Pressure in Low Viscosity Oil Miscibility Process.[J].ACS omega,2024,9(28):30131-30141.

[8] Keyvani F ,Safaei A ,Kazemzadeh Y , et al.Impact of nanopore confinement on phase behavior and enriched gas minimum miscibility pressure in asphaltenic tight oil reservoirs.[J].Scientific reports, 2024, 14(1):13405-13405.

[9] Chen Z ,Chen J ,Zhang X .A comprehensive review of minimum miscibility pressure determination and reduction strategies between CO_2 and crude oil in CCUS processes[J].Fuel,2025,384134053-134053.

[10] Chen Z ,Chen J ,Zhang X .A comprehensive review of minimum miscibility pressure determination and reduction strategies between CO_2 and crude oil in CCUS processes[J].Fuel,2025,384134053-134053.

[11] Wu C ,Jin L ,Zhao J , et al.Determination of Gas–Oil minimum miscibility pressure for impure CO_2 through optimized machine learning models[J].Geoenergy Science and Engineering, 2024, 2422 13216-213216.

[12] Keyvani F ,Safaei A ,Kazemzadeh Y , et al.Impact of nanopore confinement on phase behavior and enriched gas minimum miscibility pressure in asphaltenic tight oil reservoirs.[J].Scientific reports, 2024, 14(1):13405-13405.

[13] Song G ,Meng Y ,Zhang C , et al.Comprehensive Review of the Determination and Reduction of the Minimum Miscibility Pressure during CO_2 Flooding.[J].ACS omega,2024,9(13):14747-14765.

[14] Su Y ,Yang R ,Zhang L , et al.The Influence of Slim Tube Length on the Minimum Miscibility Pressure of CO_2Gas–Crude Oil[J].Processes,2024,12(4).

[15] Zengding W , Tengyu L, Shanchao L, et al.Adsorption effects on CO_2-oil minimum miscibility pressure in tight reservoirs[J]. Energy, 2024,288129815-.