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The Influence of Slim Tube Length on the Minimum Miscibility Pressure of CO_2 Gas–Crude Oil

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Abstract: This study focuses on the Bozhong 25-1 oilfield formation oil as the experimental subject, systematically investigating the influence of different slim tube lengths (1 m, 12.5 m, 20 m, and 25 m) on the minimum miscibility pressure (MMP) of the CO_2 and formation oil mixture system. Through slim tube experiments, the interaction process of CO_2 with formation oil in slim tubes of different lengths was simulated, with a particular focus on analyzing how changes in slim tube length affect the MMP. The experiments revealed an important phenomenon: as the slim tube length gradually increased from shorter dimensions, the MMP showed a decreasing trend; when the slim tube length reached 12.5 m, this trend stabilized, meaning that further increasing the slim tube length no longer led to significant changes in the MMP, with its stable value determined to be 27.86 MPa. This phenomenon can be explained within the theoretical framework of fluid dynamics and interfacial science, where several key factors play a significant role. Firstly, the flow characteristics of the fluid inside the slim tube significantly influence it; secondly, the interfacial tension between phases is also a decisive factor; lastly, the impact of the internal microstructure of the slim tube cannot be overlooked. These aspects together form the basis for understanding the impact of slim tube length on MMP and reveal the underlying mechanisms. This research is significant for deeply understanding and quantifying this effect, providing a solid theoretical basis for optimizing CO_2 flooding technology and guiding more precise operational strategies in oilfield development practices to enhance oil displacement efficiency and economic benefits.

Keywords: MMP; slim tube length; CO_2 flooding; formation oil

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1. Introduction

In low-permeability oil reservoirs, CO_2 gas injection represents a significant method for enhancing crude oil recovery. Oil displacement efficiency through CO_2 injection is largely contingent upon the injection pressure. Oil recovery efficiency may surpass 90% solely when the injection pressure surpasses the minimum miscibility pressure (MMP), facilitating infinite miscibility between the injected gas and crude oil after several interactions, thus significantly improving the mobility ratio [1]. With elevated injection pressures, the likelihood of mixing between gas and crude oil increases. Hence, precise evaluation of MMP and its influencing factors is pivotal for the enhancement of crude oil recovery via gas injection.

Presently, primary methods for MMP determination encompass slim tube tests, rising bubble apparatus, and vapor density methods, among others. Regarded as both prevalent and notably precise, the slim tube test effectively simulates the oil and gas displacement process within reservoir porous media, concurrently minimizing impacts from adverse factors like mobility and viscosity ratio differences, gravitational segregation, and rock heterogeneity. While oil recovery efficiency derived from slim tube experiments may not directly correlate with reservoir recovery outcomes, the MMP ascertained provides a representative measure of the oil and gas system under examination [2,3]. This phenomenon occurs under miscible conditions as the dynamic phase equilibrium process governing oil and gas miscibility unfolds across various media, independent of reservoir rock properties [4–6]. Although the impact of crude oil and injected gas compositions on MMP is well acknowledged, the literature on the effects of slim tube length on MMP in experimental settings remains sparse.

Recent research has indicated that slim tube length may affect the miscibility pressure between CO_2 and formation oil, yet the body of related findings remains limited [1,2]. Consequently, this study focuses on CO_2 miscible displacement in the Bozhong 25-1 reservoir to investigate the effect of slim tube length on the minimum miscibility pressure (MMP) within the CO_2-formation oil system. This investigation examines the influence of slim tube length on MMP and oil recovery factors, incorporating a comparative analysis. Additionally, the study seeks to elucidate the underlying physical mechanisms, offering theoretical insights and guidance for optimizing CO_2 oil recovery strategies. Such insights could significantly enhance crude oil recovery factors.

The novelty of this study lies in systematically exploring the impact of slim tube length on MMP and its mechanisms, filling the gap in existing research in this field. Through comprehensive analysis, this paper not only reveals the relationship between slim tube length and MMP but also proposes new approaches to optimizing CO_2 displacement strategies, which has significant theoretical and practical implications for enhancing the recovery rate of low-permeability reservoirs.

2. CO_2 Minimum Miscibility Pressure Slim Tube Experiment

2.1. Experimental Samples

A crude oil sample was collected from the separator at the Bozhong 25-1 reservoir's Sha 2 section well. Dalian Date formulated the associated gas sample based on its composition. Formation fluids were reconstituted in accordance with "Methods for Analysis of Fluid Properties in Oil and Gas Reservoirs [7], based on an original formation pressure of 30 MPa, temperature of 127 °C, and a gas–oil ratio of 85.6 m^3/m^3. High-temperature and high-pressure physical property experiments were then conducted on the reconstituted samples using a pressure-volume-temperature (PVT) apparatus to verify compliance with standards. Key assessment indicators comprised gas–oil ratio, saturation pressure, and the viscosity and density of the formation crude oil.

Aligned with the target block's formation conditions, dehydrated crude oil was processed into formation oil samples. Preparation conditions for the formation oil samples are detailed in Table 1. Composition of compound formation oil in Table 2.

Table 1. Conditions for oil sample preparation.

Block	Formation Temperature (°C)	Formation Pressure (MPa)	Formation Oil and Gas Ratio (m^3/m^3)
Bozhong 25-1 Sha 2 Section	127	30	85.6

Table 2. Composition of compound formation oil.

Components	Mole Fraction (%)
CO_2	1.35
N_2	0
C_1	31.41
C_2	5.69

Table 2. *Cont.*

Components	Mole Fraction (%)
C_3	2.17
C_4	1.76
C_5	0.56
C_6	0.59
C_{7+}	56.46
Relative molecular mass of C_{7+} ($g \cdot mol^{-1}$)	220.9

2.2. Experimental Reagents and Equipment

Prepared according to oil and gas data in a high-temperature, high-pressure PVT analyzer. High-purity CO_2 (purity > 99.99%, Dalian Special Gases Co., Ltd., Dalian, China) serves as the experimental gas.

Experimental equipment: high temperature and high pressure PVT analyzer (manufactured by Yangzhou Huabao Petroleum Instrument Co., LTD., Yangzhou, China; Temperature: 200 °C, Pressure: 70 MPa); The K-7000 Steam Pressure Permeability Analyzer (manufactured by KNAUER GmbH in Germany, Berlin, Germany), Glass Piston Syringes supplied (manufactured by KNAUER GmbH in Germany, Berlin, Germany), Isco-260d high precision displacement pump (manufactured by Teledyne Isco Company, Lincoln, NE, USA; flow rate: 0.001~107 mL/min; Pressure: 0.07~51.71 MPa); HW-G high temperature two-phase displacement system (manufactured by China Hai'an Petroleum Scientific Research Instrument Co., LTD., Hai'an, China; Temperature: 300 °C); High precision pressure sensor (manufactured by Guangzhou Senas Instrument Co., LTD., Guangzhou, China; range from 0 to 70 MPa); A thin tube with a length of 1 m; A thin tube with a length of 12.5 m; A fine tube with a length of 20 m; A thin tube with a length of 25 m (self-made); W-NK-0.5B Wet gas flowmeter (range from 0.016 to 5 L/min, Shinagawa, Japan); Injection piston container (manufactured by Yangzhou Huabao Petroleum Instrument Co., LTD., Yangzhou, China; capacity of the container is set at 2000 mL, operating pressure is set at 70 MPa), pipeline, test tube, stopwatch and other necessary apparatus.

2.3. Experimental Method

The main parameters of the physical simulation device model used for miscible displacement in this study are shown in Table 3. The process flow of the slim tube experiment is shown in Figure 1. Multiple slim tube oil displacement experiments are conducted according to the displacement scheme, to obtain oil displacement efficiency under different displacement pressures.

Table 3. Slim tube model parameters.

Length (m)	Outside Diameter (mm)	Inside Diameter (mm)	Filling Material	Gas Permeability (mD)	Porosity (%)
1	6	4	Micro glass beads	4026	40
12.5	6	4	Micro glass beads	5277	39
20	6	4	Micro glass beads	5017	33
25	6	4	Micro glass beads	4420	37

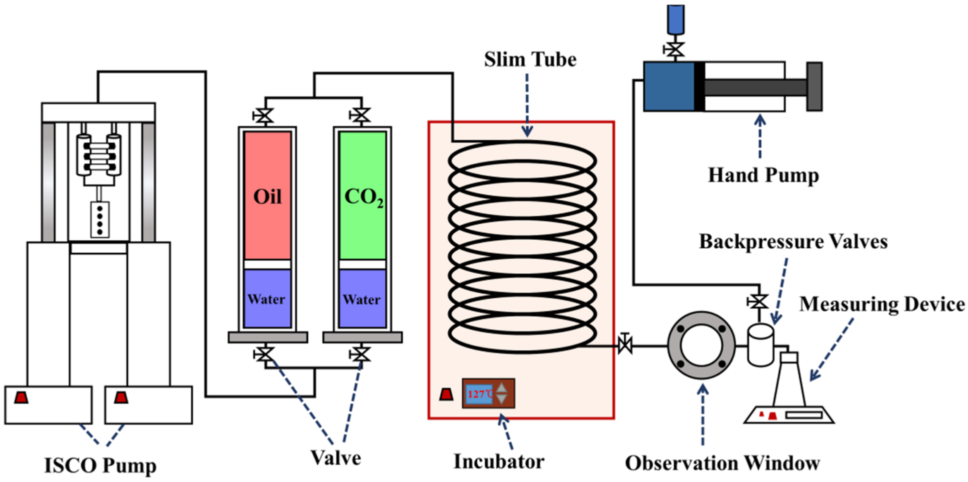

Figure 1. Flowchart of the slim tube experiment.

In the slim tube experiments, regardless of miscibility, when 1.2 pore volumes (PV) are injected, the recovery rate generally does not increase further, and this rate is equal to or close to the total recovery rate. Therefore, the final recovery rate at 1.2 PV injection is generally used as the basis for comparison in each displacement experiment. The formula for calculating the recovery rate is

$$\text{Oil displacement efficiency} = \frac{\text{Volume of produced oil} \times \text{Volume coefficient}}{\text{Saturated oil volume}} \times 100\% \quad (1)$$

$$\text{Volume coefficient} = \frac{\text{Volume of formation oil}}{\text{Volume of degassed formation oil at surface}} \quad (2)$$

Formation crude oil samples and CO_2 injection gas were used to conduct seven different slim tube experiments under varying displacement pressures at a formation temperature of 127 °C.

2.4. Experimental Procedure

In the experiment, special attention was paid to preventing leakage, especially gas leakage at high temperatures. The specific experimental steps are as follows:

(1) Cleaning pipeline

Before starting the cleaning with petroleum ether, maintain the thermostatic box at the formation temperature of 127 °C. After opening the pipeline switch, perform a constant flow rate displacement at a low pressure with a flow rate of 0.45 mL/min to saturate the entire pipeline and displace air and other impurities from the system. When a continuous flow of colorless and transparent liquid (petroleum ether) appears at the outlet, it indicates that the pipeline has been cleaned. Then, stop the pump and close the petroleum ether piston container.

(2) Saturating dead oil

Open the upstream and downstream of the dead oil container and saturate the dead oil at a pressure of 18 MPa. The displacement flow rate remains at 0.45 mL/min throughout the process. To ensure no degassing occurs during live oil saturation, this process is carried out above the bubble point pressure. After saturating the dead oil (approximately 1.2 PV), close the outlet of the dead oil piston container.

(3) Saturating formation oil

Slowly open the outlet valve of the crude oil piston container and the inlet valve of the slim tube. Displace at a constant flow rate of 0.45 mL/min. When the calculated oil–gas ratio reaches 85.6 m^3/m^3, the saturation of live oil is complete. Then, close the outlet of the live oil piston container.

(4) CO_2 displacement of crude oil

Slowly open the outlet valve of the CO_2 container and the inlet valve of the slim tube. Displace the crude oil with CO_2 at a flow rate of 0.125 cm^3/min. During this process, record the pressure, cumulative oil displacement volume, and production of oil and gas approximately every 0.1 PV. When the displacement volume reaches 1.2 PV, stop the displacement and close the upstream and downstream of the CO_2 container.

This translation provides a detailed step-by-step guide to the experimental procedure, focusing on cleanliness, accuracy, and safety in handling and displacing various substances.

3. Experimental Results and Analysis

Slim tube experiments were conducted using different tube lengths (1 m, 12.5 m, 20 m, 25 m) under seven different displacement pressures, with the experimental temperature maintained at 127 °C. It is generally considered that when the final recovery rate exceeds 90%, the injected gas and crude oil reach a miscible state. The data point where the recovery rate reaches 90% is used as an inflection point for linear fitting, and the intersection of the two lines represents the MMP for the injected gas and crude oil.

3.1. Experimental Results for CO_2 Flooding in 1 m Long Slim Tube

Figure 2 shows the oil recovery efficiency graph for the 1 m slim tube CO_2 displacement. As can be seen from Figure 2, under different displacement pressures, the crude oil recovery factor gradually increases with the increase in CO_2 injection volume. An inflection point appears around 0.9 PV, and when the injection volume reaches 1.2 PV, the oil recovery efficiency does not change anymore. The final recovery rates are, respectively, 44.14%, 55.17%, 66.21%, 75.03%, 86.07%, 90.48%, and 94.90%.

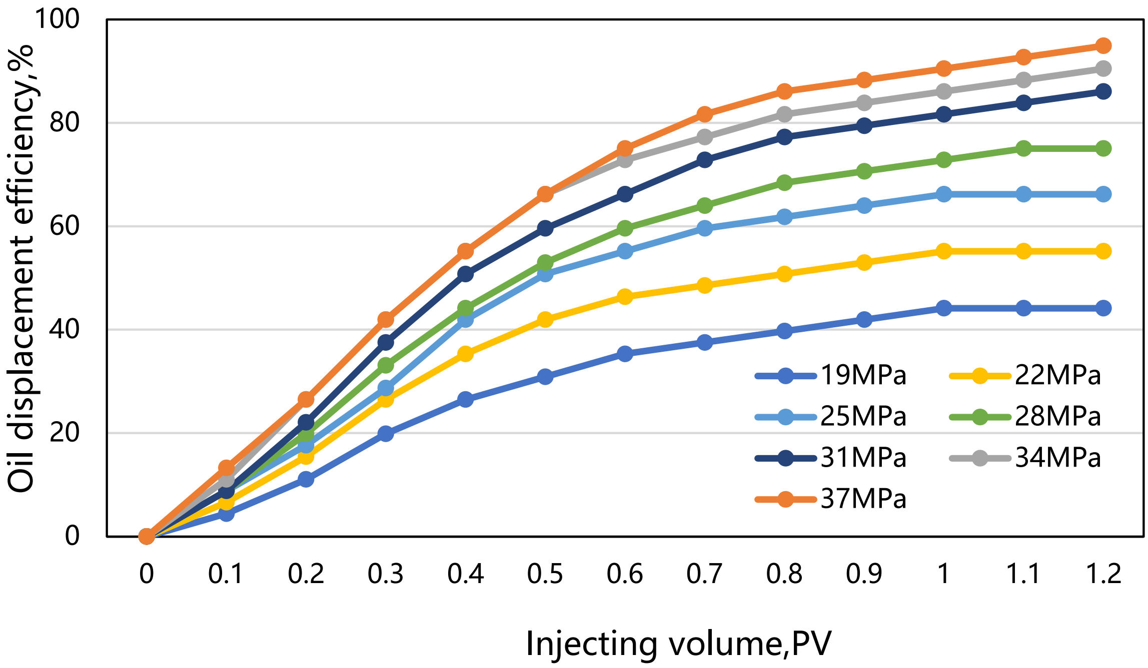

Figure 2. The oil displacement efficiency for CO_2 flooding in 1 m long slim tube.

This translation presents the experimental results and the analysis approach, highlighting the relationship between CO_2 injection, recovery rates, and the determination of MMP in a 1 m slim tube setup.

Based on Table 4 and Figure 3, it is evident that the efficiency of displacement increases with rising displacement pressure. A significant inflection in the curve representing the relationship between recovery rate and displacement pressure occurs when the displacement pressure reaches 30 MPa. When the displacement pressure exceeds 34 MPa, the recovery rate is greater than 90%, indicating miscible displacement. Even if the displacement pressure continues to increase, the rate of increase in recovery is minimal, and the curve tends to flatten out. Above a displacement pressure of 31 MPa, partial miscibility occurs in the reservoir. The closer the displacement pressure is to the MMP, the higher the recovery rate.

Table 4. Experimental results for CO_2 flooding in 1 m long slim tube.

No.	Displacement Pressure (MPa)	Temperature (°C)	Recovery Rate When Injecting 1.2 PV (%)	Evaluation
1	19	127	44.14	immiscible
2	22	127	55.17	immiscible
3	25	127	66.21	immiscible
4	28	127	75.03	immiscible
5	31	127	86.07	immiscible
6	34	127	90.48	miscible
7	37	127	94.90	miscible

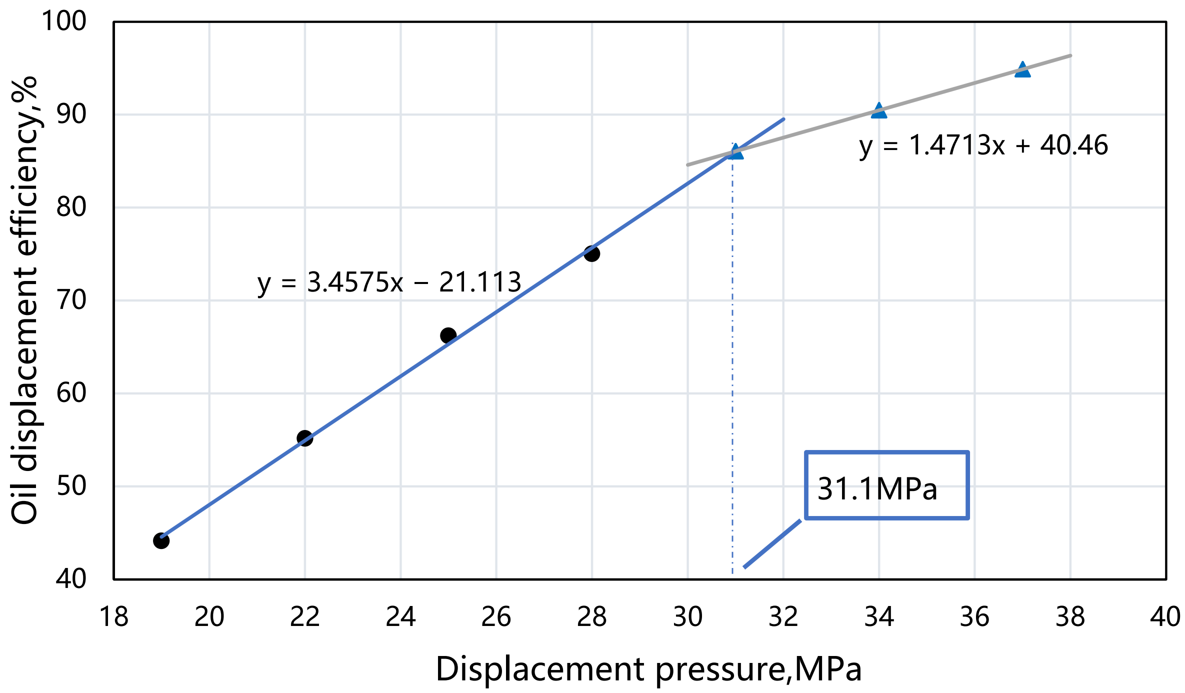

Figure 3. The minimum miscibility pressure for CO_2 flooding in 1 m long slim tube.

By analyzing the slim tube experimental data and plotting the curves based on the final crude oil recovery factors at various injection pressures, as shown in Figure 3, a linear fit is performed for the data before and after miscibility, and the intersection point of these lines represents the MMP. Therefore, the MMP for CO_2–crude oil as measured by the 1 m slim tube is determined to be 31.1 MPa.

This translation provides a detailed description of the analysis of the experimental data, emphasizing the relationship between displacement pressure, recovery rate, and the determination of MMP in the context of CO_2–crude oil miscible displacement.

3.2. Experimental Results for CO_2 Flooding in 12.5 m Long Slim Tube

Figure 4 shows the oil recovery efficiency graph for the 12.5 m slim tube CO_2 displacement. As can be seen from Figure 4, under different displacement pressures, the crude oil recovery factor gradually increases with the increase in CO_2 injection volume. An inflection point appears around 0.9 PV, and when the injection volume reaches 1.2 PV, the oil recovery efficiency does not change anymore. The final recovery rates are, respectively, 44.37%, 59.67%, 72.75%, 85.23%, 92.16%, 94.55%, and 96.69%.

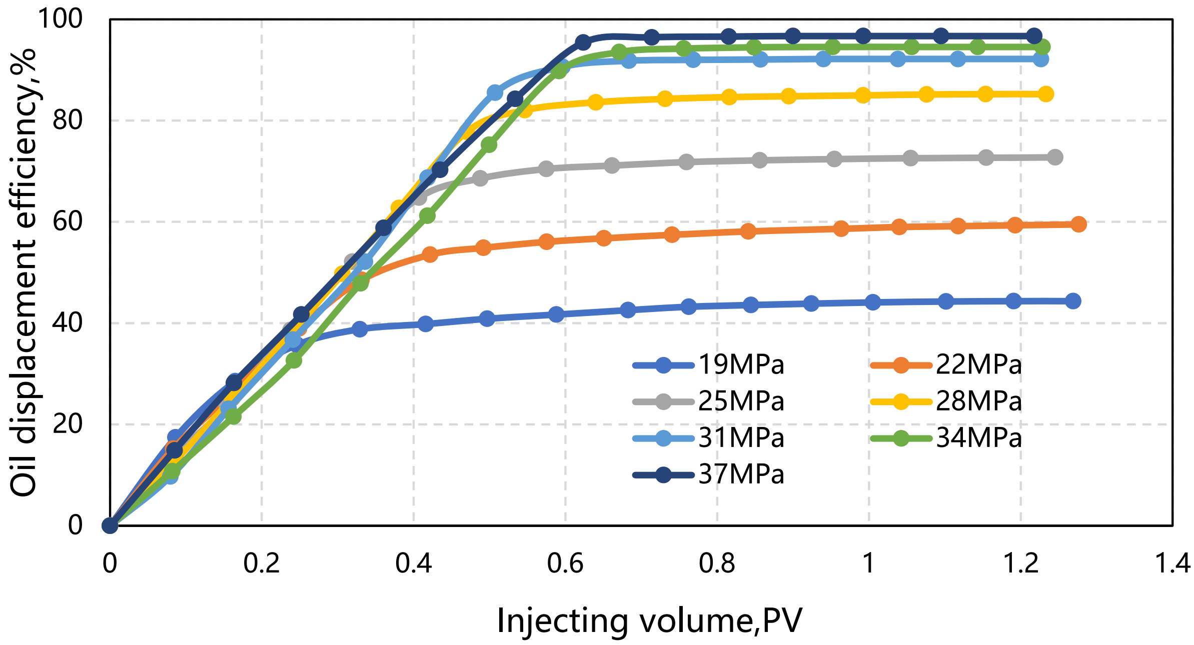

Figure 4. The oil displacement efficiency for CO_2 flooding in 12.5 m long slim tube.

From Table 5 and Figure 5, it can be observed that the oil displacement efficiency increases with the rise in displacement pressure. A significant inflection in the curve representing the relationship between recovery rate and displacement pressure occurs when the displacement pressure equals 28 MPa. When the displacement pressure exceeds 31 MPa, the recovery rate is greater than 90%, indicating miscible displacement. Even with further increases in displacement pressure, the increment in recovery rate remains small, and the curve tends to flatten out. Above a displacement pressure of 28 MPa, partial miscibility occurs in the reservoir. The closer the displacement pressure is to the MMP, the higher the recovery rate.

Table 5. Experimental results for CO_2 flooding in a 12.5 m long slim tube.

No.	Displacement Pressure (MPa)	Temperature (°C)	Recovery Rate When Injecting 1.2 PV (%)	Evaluation
1	19	127	44.37	immiscible
2	22	127	59.67	immiscible
3	25	127	72.75	immiscible
4	28	127	85.23	immiscible
5	31	127	92.16	miscible
6	34	127	94.55	miscible
7	37	127	96.69	miscible

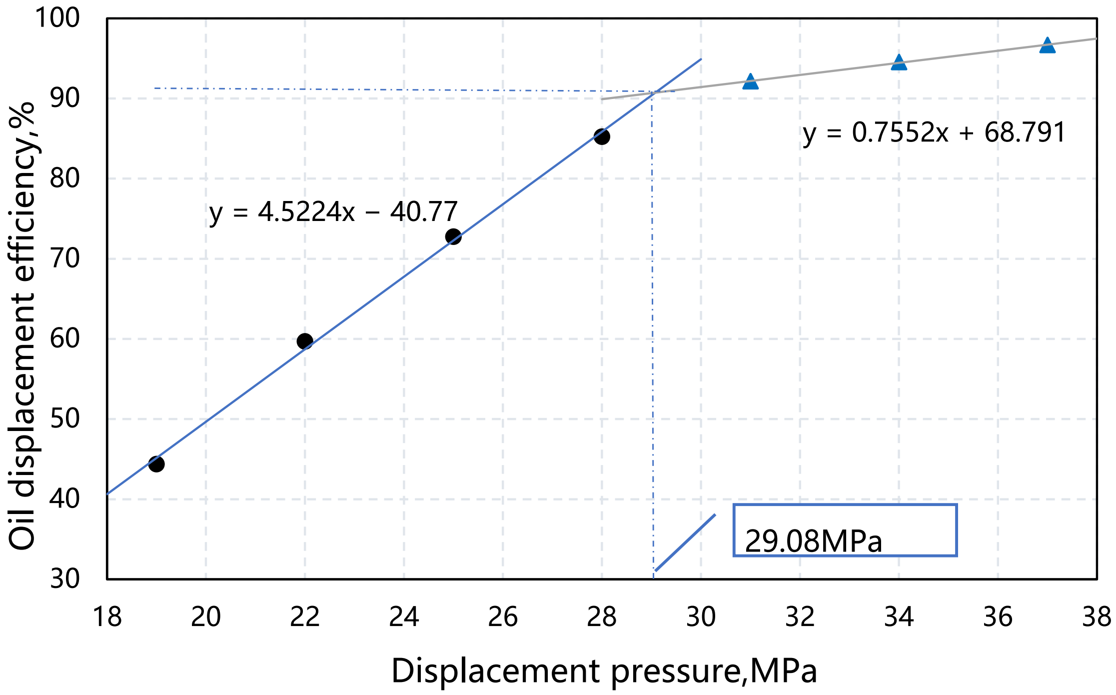

Figure 5. The minimum miscibility pressure for CO_2 flooding in 12.5 m long slim tube.

By analyzing the slim tube experimental data and plotting the curves based on the final crude oil recovery factors at various injection pressures, as shown in Figure 5, a linear fit is performed for the data before and after miscibility, and the intersection point of these lines represents the MMP. Therefore, the MMP for CO_2–crude oil as measured by the 12.5 m slim tube is determined to be 29.08 MPa, as detailed in Table 5.

3.3. Experiment Results for CO_2 Flooding in 20 m Long Slim Tube

Using the same experimental method as the 12.5 m slim tube experiments, the 20 m slim tube maintained the same experimental temperature and displacement pressures. The final recovery rates obtained are shown in Table 6. Figure 6 presents the oil recovery efficiency graph for the 20 m slim tube CO_2 displacement. As seen in Figure 6, under different displacement pressures, the crude oil recovery factor gradually increases with the increase in CO_2 injection volume. An inflection point appears around 0.9 PV, and when the injection volume reaches 1.2 PV, the oil recovery efficiency does not change anymore. The final recovery rates are, respectively, 47.14%, 58.64%, 77.01%, 91.62%, 93.36%, 96.63%, and 97.40%.

Table 6. Experimental results for CO_2 flooding in 20 m long slim tube.

No.	Displacement Pressure (MPa)	Temperature (°C)	Recovery Rate When Injecting 1.2 PV (%)	Evaluation
1	19	127	47.14	immiscible
2	22	127	58.64	immiscible
3	25	127	77.01	immiscible
4	28	127	91.62	miscible
5	31	127	93.36	miscible
6	34	127	96.63	miscible
7	37	127	97.40	miscible

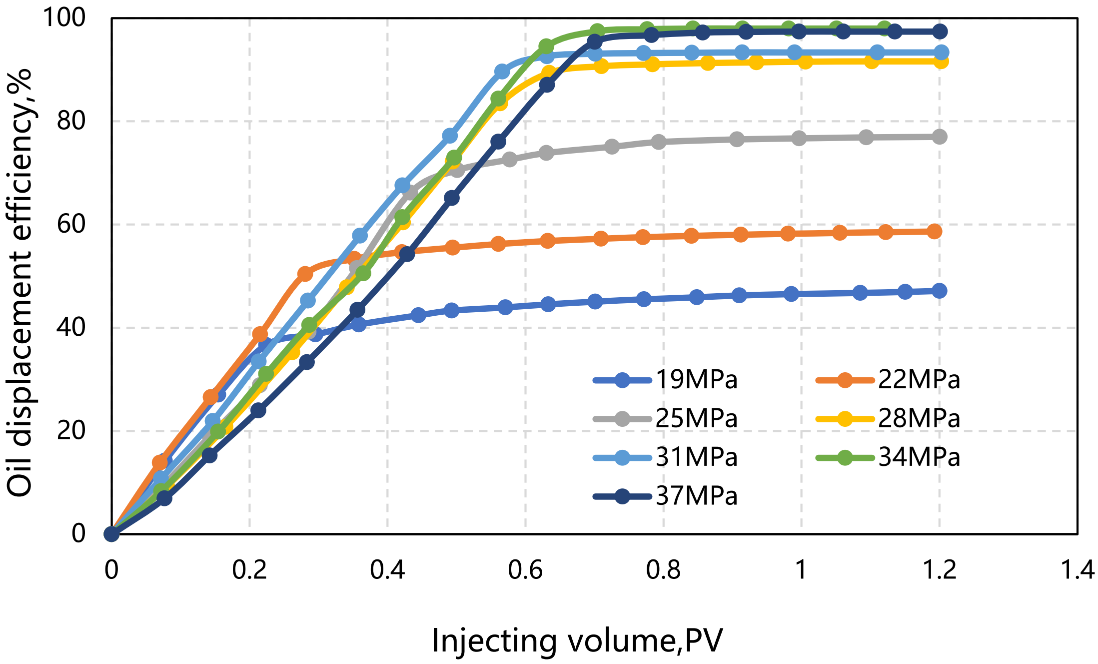

Figure 6. The oil displacement efficiency for CO_2 flooding in 20 m long slim tube.

From Table 6 and Figure 7, it can be observed that the oil displacement efficiency increases with the rise in displacement pressure. A significant inflection in the curve representing the relationship between recovery rate and displacement pressure occurs when the displacement pressure equals 25 MPa. When the displacement pressure exceeds 28 MPa, the recovery rate is greater than 90%, indicating miscible displacement. Even with further increases in displacement pressure, the increment in recovery rate remains small, and the curve tends to flatten out. Above a displacement pressure of 25 MPa, partial miscibility occurs in the reservoir. The closer the displacement pressure is to the MMP, the higher the recovery rate, meaning that higher pressures are closer to miscibility. This pressure range can be considered as near-miscible displacement.

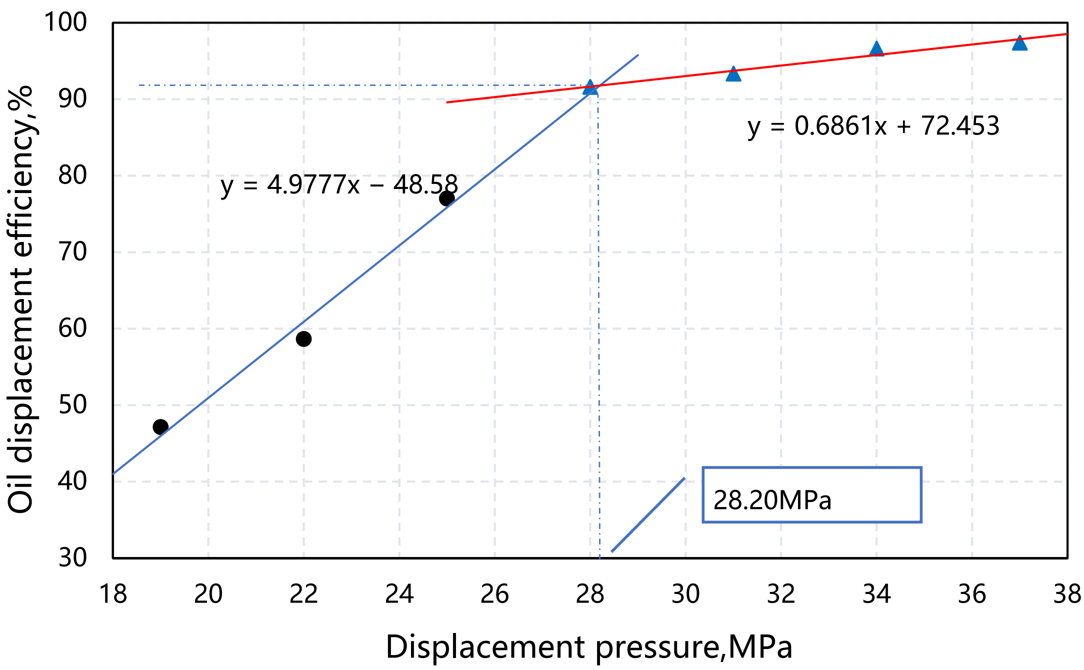

Figure 7. The minimum miscibility pressure for CO_2 flooding in 20 m long slim tube.

By analyzing the slim tube experimental data and plotting the curves based on the final crude oil recovery factors at various injection pressures, as shown in Figure 7, a linear fit is performed for the data before and after miscibility, and the intersection point of these lines represents the MMP. Therefore, the MMP for CO_2–crude oil as measured by the 20 m slim tube is determined to be 28.2 MPa, as detailed in Table 6.

3.4. Experiment Results for CO_2 Flooding in a 25 m Long Slim Tube

Maintaining the same experimental conditions, the final recovery rates obtained for the 25 m slim tube are shown in Table 7. Figure 8 presents the oil recovery efficiency graph for the 25 m slim tube CO_2 displacement. As seen in Figure 8, under different displacement pressures, the crude oil recovery factor gradually increases with the increase in CO_2 injection volume. An inflection point appears around 0.9 PV, and when the injection volume reaches 1.2 PV, the oil recovery efficiency does not change anymore. The final recovery rates are, respectively, 50.67%, 62.34%, 79.88%, 92.57%, 95.46%, 97.16%, and 98.85%.

Table 7. Experimental results for CO_2 flooding in 25 m long slim tube.

No.	Displacement Pressure (MPa)	Temperature (°C)	Recovery Rate When Injecting 1.2 PV (%)	Evaluation
1	19	127	50.67	immiscible
2	22	127	62.34	immiscible
3	25	127	79.88	immiscible
4	28	127	92.57	miscible
5	31	127	95.46	miscible
6	34	127	97.16	miscible
7	37	127	98.85	miscible

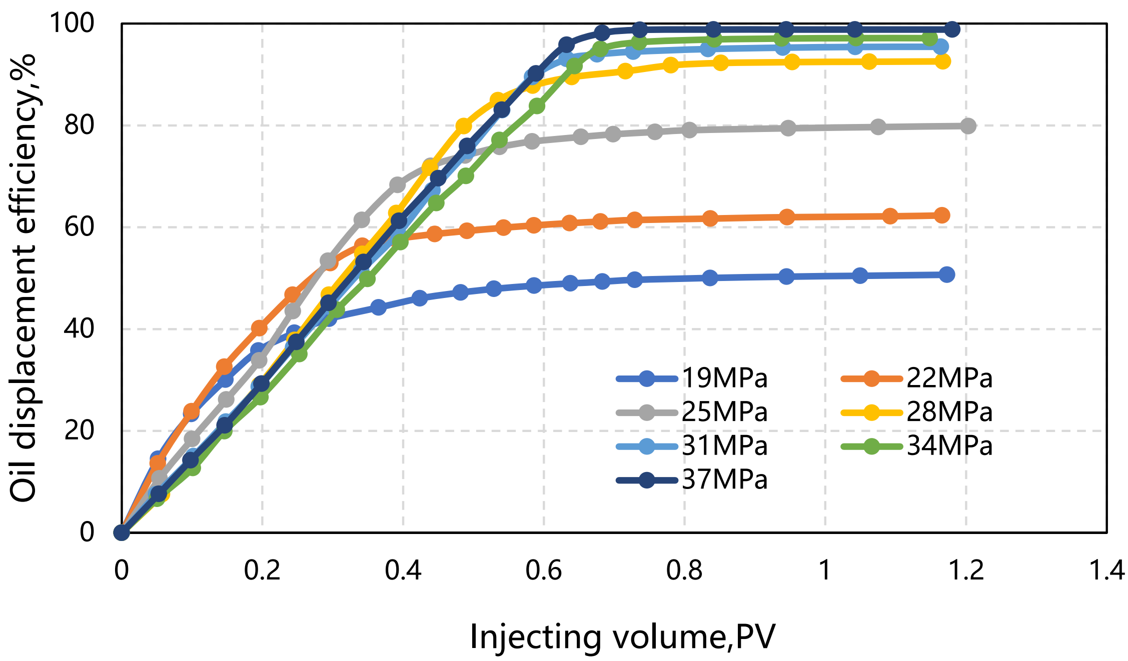

Figure 8. The oil displacement efficiency for CO_2 flooding in 25 m long slim tube.

From Table 7 and Figure 9, it is evident that the oil displacement efficiency increases with increasing displacement pressure. A significant inflection in the curve representing the relationship between recovery rate and displacement pressure occurs when the displacement pressure equals 25 MPa. When the displacement pressure exceeds 28 MPa, the recovery rate is greater than 90%, indicating miscible displacement. Even if the displacement pressure continues to increase, the increment in recovery rate remains small, and the curve tends to flatten out. Above a displacement pressure of 25 MPa, partial miscibility occurs in the reservoir. The closer the displacement pressure is to the MMP, the higher the recovery rate, meaning that higher pressures are closer to miscibility. This pressure range can be considered as near-miscible displacement.

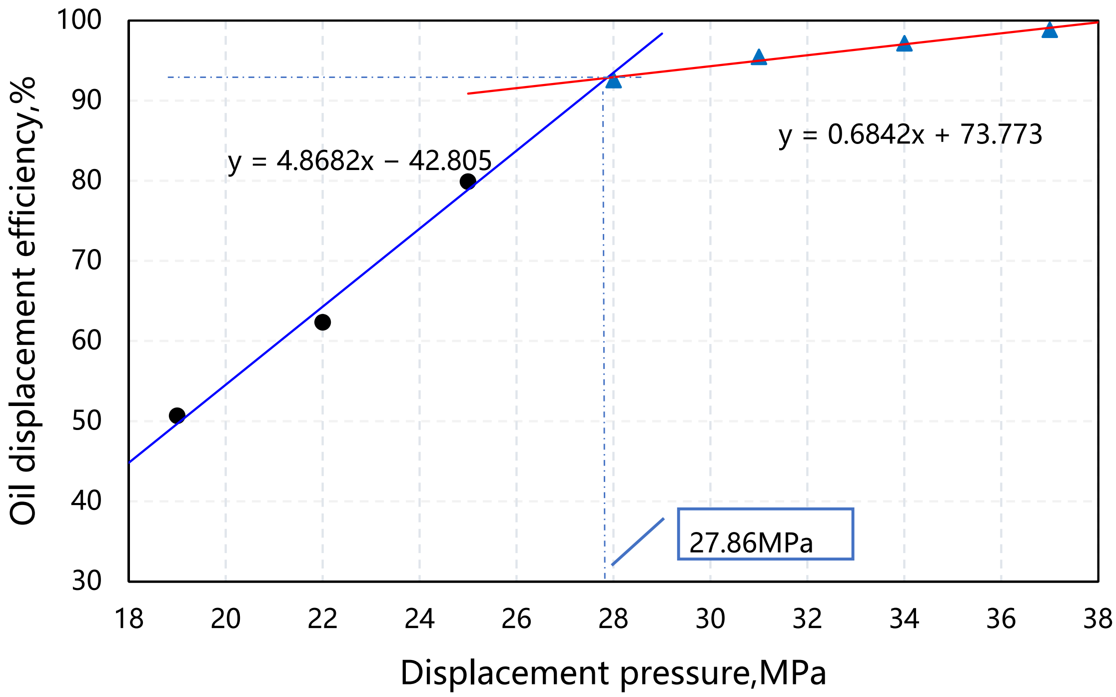

Figure 9. The minimum miscibility pressure for CO_2 flooding in 25 m long slim tube.

By analyzing the slim tube experimental data and plotting the curves based on the final crude oil recovery factors at various injection pressures, as shown in Figure 9, a linear fit is performed for the data before and after miscibility, and the intersection point of these lines represents the MMP. Therefore, the MMP for CO_2–crude oil as measured by the 25 m slim tube is determined to be 27.86 MPa, as detailed in Table 7.

3.5. Analysis of the Impact of Different Slim Tube Lengths on MMP and Final Recovery Rate

Figures 10 and 11 show the oil recovery efficiency curves for different slim tube lengths at non-miscible (22 MPa) and miscible (31 MPa) points. From Figure 10, it is evident that before reaching miscibility, the longer the slim tube, the higher the oil recovery efficiency when the same pore volume multiple of CO_2 is injected. As shown in Figure 11, at the point of miscibility, when the slim tube length exceeds 12.5 m, the oil recovery efficiency is similar for the same pore volume multiple of CO_2 injection, while at a slim tube length of 1 m, the efficiency is significantly different.

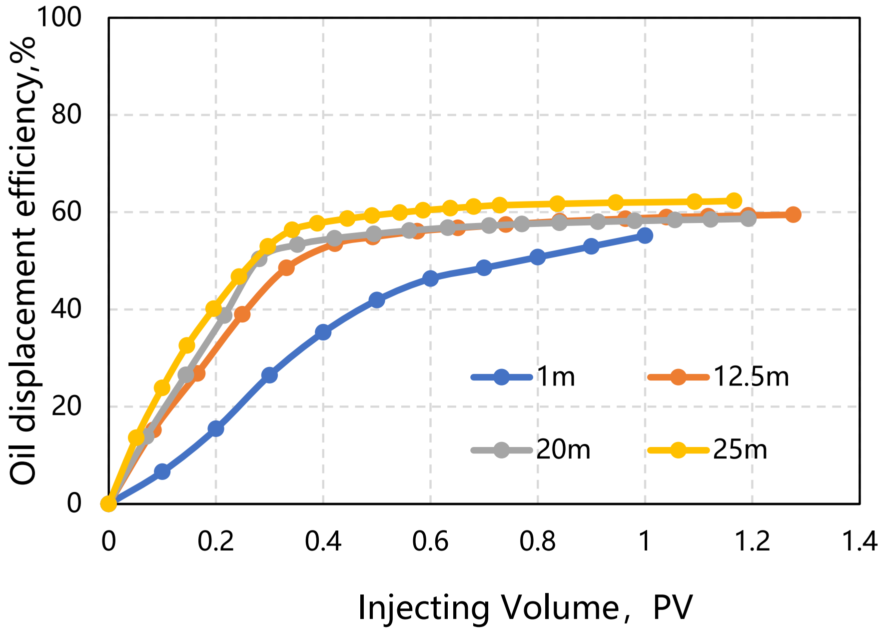

Figure 10. Change in oil displacement efficiency at the immiscible pressure point (22 MPa).

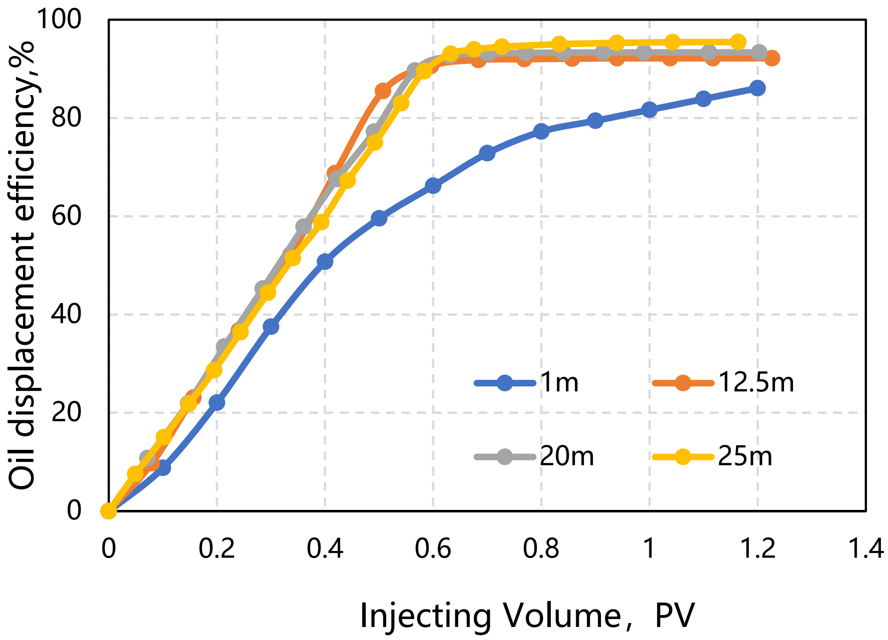

Figure 11. Change in oil displacement efficiency at the miscible pressure point (31 MPa).

From the CO_2 displacement experiment results using slim tubes of various lengths, it is observed that the MMP for CO_2–crude oil gradually decreases with increasing slim tube length. As depicted in Figure 12, through linear fitting of the experimental data, an empirical formula relating MMP to slim tube length is obtained: $y = 0.0033x^2 - 0.2214x + 31.32$, showing a high degree of correlation. This formula provides a reference for estimating the MMP in miscible CO_2 displacement experiments with different slim tube lengths. As shown in Figure 12, the MMP decreases from 31.1 MPa to 27.86 MPa with increasing slim tube length. This decrease is attributed to the increased gas–liquid contact area with longer tubes, enhancing mass transfer between bubbles and liquid, improving solubility, and thereby reducing the MMP of CO_2-formation oil.

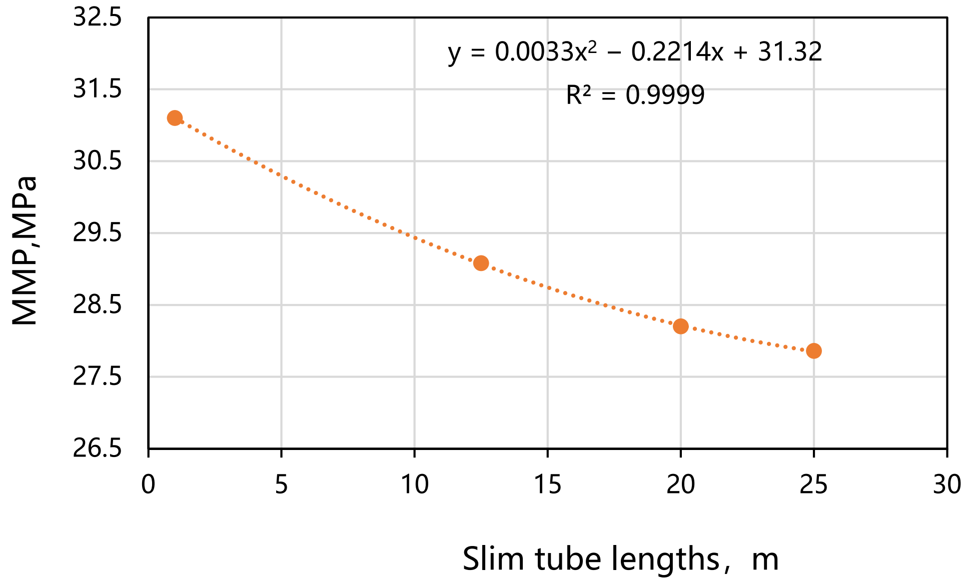

Figure 12. Minimum miscibility pressure of CO_2 flooding for slim tube lengths.

In summary, from the miscible gas injection experiments using slim tubes of different lengths as shown in Figure 13 and Table 8, it can be concluded that with a fixed slim tube length, a higher injection pressure results in a higher crude oil recovery factor and later gas breakthrough time. When changing the slim tube length, the MMP gradually decreases with an increase in tube length, and the rate of decrease slows down. Additionally, the crude oil recovery factor improves under different injection pressures. Therefore, the longer the distance between the injection and production wells, the higher the miscible gas injection rate and the greater the crude oil recovery factor. This is because CO_2 has more time to interact with the crude oil as it flows through the reservoir, thus having more opportunities to reduce the miscibility pressure and mix with the crude oil. This effect might be more pronounced in simulated slim tubes, as slim tube forces are more significant at smaller scales. This highlights the importance of fluid physicochemical properties, well spacing, and slim tube effects in enhancing crude oil recovery in reservoirs. These patterns are significant for optimizing CO_2 oil recovery strategies and improving the economic efficiency of oil fields.

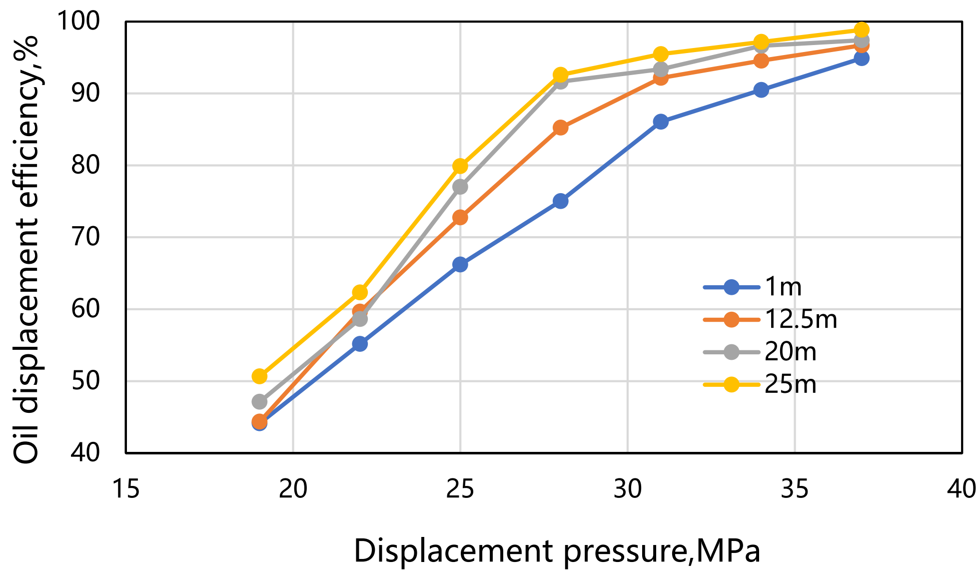

Figure 13. Oil displacement efficiency at different slim tube lengths and displacement pressures.

Table 8. Results for the MMP from experiments with slim tubes of different lengths.

Length (m)	Temperature (°C)	Recovery Rate When Injecting 1.2 PV (%)	MMP (MPa)
1	127	94.9	31.1
12.5	127	96.69	29.08
20	127	97.4	28.2
25	127	98.8	27.86

3.6. The Mechanism of the Impact of Slim Tube Length on Minimum Miscibility Pressure

The mechanism by which slim tube length affects the MMP of CO_2 and formation oil involves several complex factors, primarily as follows:

1. Fluid dynamic effect: The flow of fluids in the thin tube can be described by Navier–Stokes Equations, which consider the effects of friction caused by fluid viscosity on flow. In the thin tube, the fluid dynamic effect is mainly characterized by Reynolds Number. The ratio of Renault is the ratio of inertial force and viscosity, and it is used to determine the flow or turbulence. Increase in the length of the thin tube will increase the length of the fluid flow, which may increase the total friction of the fluid, leading to changes in fluid flow rate and the change of the flow mode. For example, shorter tubes may support higher flow velocity and stratum flow status, and longer thin tubes may cause flow rate reduction and flow mode turbulence, which affects the interaction efficiency between CO_2 and strata oil, then affecting MMP [8].

2. Interfacial Tension: The changes in the interface tension can be described by the Young–Laplace Equation, which illustrates the relationship between the curved tension and pressure difference. Changes in the length of the tube may affect the interface curvature between CO_2 and stratigraphic oil, which will affect the tension of the interface. Decreasing the tension of the phase interface promotes mixing between the two phases. Therefore, if the increase in the length of the tube is reduced, the tension of the phase interface can be reduced, which may help reduce MMP. On the other hand, if the tension of the phase interface increases, this may inhibit the mixing between the two phases, resulting in the improvement of MMP [9–12].

3. Internal Microstructure of the Tube: Microstructures inside fine tubes, such as porosity and pore size distribution, are critical for fluid flow and interactions. Changes in the internal structure of a thin tube can be described by Darcy's law and permeability concepts, which illustrate the relationship between the flow rate of fluid flow in a porous medium and the driving pressure. An increase in the length of the fine tube may lead to changes in the microstructure in the flow path: for example, an increase in path length may lead to more pore channels participating in the flow, which may improve or hinder the contact and mixing between CO_2 and formation oil, which in turn affects MMP.

4. Changes in Mass Transfer Pathways: Mass transfer efficiency is critical for miscible behavior between CO_2 and formation oil. An increase in the length of the tube may change the flow characteristics and thus the mass transfer path along the wall of the tube and along the center of the tube. The effect of a change in the length of a thin tube on the mass transfer efficiency can be analyzed by diffusion equations (e.g., Fick's laws of diffusion), which describe the diffusion process of a substance driven by a concentration gradient. Increased tube length can lead to more complex mass transfer paths and increased mixing resistance, which can affect the rate of material transfer to the interface, which in turn affects MMP.

5. Increased Residence Time: The residence time of fluids in the tube increases with the length of the tube, enhancing the duration of mixing and contact, thereby influencing the MMP.

6. Properties of Formation Oil: The physical and chemical characteristics of formation oil, such as composition and viscosity, are also key factors affecting the minimum miscible pressure. The oil phase with higher viscosity may lead to the blockage of fluid flow, and different compositions may affect the solubility of and interaction with CO_2. The change in

the length of the thin tube may affect the flow and distribution of formation oil in the thin tube, and thus affect the miscible pressure [13].

In the slim tube model, the impact of tube length on MMP can be described as follows: Shorter tubes may require higher pressure to achieve miscibility, as the time for complete mixing of CO_2 solvent and oil is shorter. Longer tubes allow miscibility at lower pressures due to increased contact time, allowing more complete mixing. To illustrate this concept, two different lengths of slim tubes are depicted, with pressure gradients along each tube, indicating where miscibility is achieved in each case. The illustration shows two slim tubes of different lengths and the position within each tube where miscibility occurs.

Figure 14 illustrates the mechanism by which tube length influences the MMP in CO_2-enhanced oil recovery processes, with a focus on the formation of a miscible zone between CO_2 and crude oil. This visualization captures the evolution of the miscible zone across tubes of varying lengths (1 m, 12.5 m, 20 m, and 25 m), highlighting how CO_2 and crude oil mixing efficiency improves with increased tube length, leading to a reduction in the MMP required for effective oil recovery.

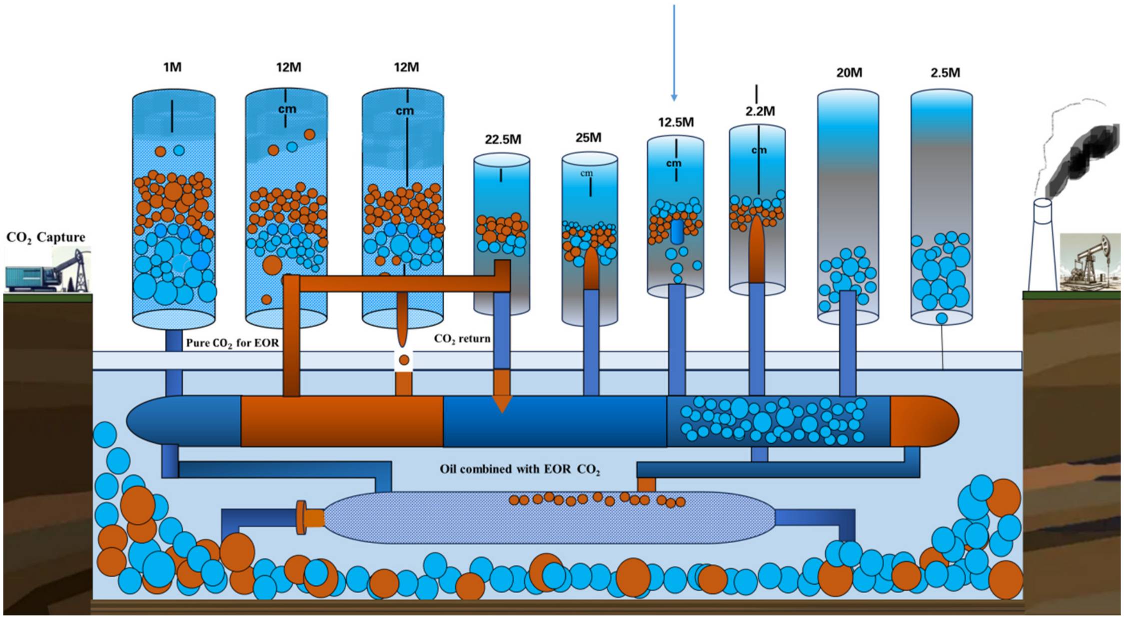

Figure 14. Schematic diagram of the influence of slim tube length on minimum miscibility pressure.

Shorter Tubes: A smaller miscible zone with denser CO_2 molecules, indicating higher pressure requirements for achieving miscibility with crude oil. Longer Tubes: An expanding miscible zone where CO_2 molecules are more evenly distributed and thoroughly mixed with the oil molecules, symbolizing more efficient miscibility at lower pressures.

This schematic representation serves as an insightful guide into the dynamics of CO_2 injection and its interaction with crude oil within the context of underground oil reservoirs, emphasizing the critical role of the miscible zone in enhancing oil recovery efficiency.

In summary, the impact of slim tube length on the MMP is a comprehensive process involving the interaction of multiple factors. A deeper investigation into these mechanisms can provide a theoretical basis for optimizing CO_2-enhanced oil recovery (EOR) techniques, as well as offer more effective operational guidance for oilfield development.

4. Conclusions

(1) Studies on the impact of slim tube length on the MMP for CO_2-formation oil were conducted using slim tubes of 1 m, 12.5 m, 20 m, and 25 m in length. The results indicate that the MMPs for CO_2-formation oil are 31.1 MPa, 29.08 MPa, 28.20 MPa, and 27.86 MPa for tubes of lengths 1 m, 12.5 m, 20 m, and 25 m, respectively.

(2) The length of the slim tube significantly influences the MMP. With increasing slim tube length, the MMP initially decreases and then tends to stabilize. This phenomenon is closely related to the fluid dynamics within the slim tube and the effects of the phase interface.

(3) Longer slim tubes increase the contact area and time between CO_2 and oil, facilitating mass transfer between them and promoting mixing. This allows miscibility to be achieved at lower pressures. The longer the slim tube, the longer the residence time of the fluid inside it, improving the mixing efficiency of CO_2 and oil, and thus reducing the pressure required to reach the MMP.

(4) Based on these research findings, the development of more precise models and algorithms to predict and control the MMP will further enhance the efficiency and cost-effectiveness of CO_2 EOR techniques. These experimental results not only enrich the theoretical foundation of the CO_2 EOR field but also provide important guidance for optimizing CO_2 EOR parameters in practical applications.

(5) Exploring the impact of slim tube length on MMP, it can be better extended to practical applications. First of all, it can improve oilfield development efficiency. This investigation helps to accurately predict the optimal pressure conditions to achieve CO_2 flooding under specific field conditions, so as to optimize CO_2 injection strategies and design more effective CO_2 injection plans, thereby improving oil recovery, reducing resource waste, and maximizing cost effectiveness. Secondly, it also improves the efficiency of CO_2 storage, especially in the secondary utilization of oil and gas fields after abandonment, which can provide a safer and more effective parameter design basis for CO_2 storage, reduce greenhouse gas emissions, and promote environmental protection.

(6) Through studying the changes in MMP under different formation conditions, some basis is provided for future research directions. Future research can explore the effect of different slim tube diameters on MMP. The variation in slim tube diameter may affect the flow properties of fluids in the slim tube, thereby affecting the determination of the mixed-phase pressure. Studying this effect can not only improve the accuracy of MMP prediction, but also contribute to a better understanding of the microscopic mechanisms of CO_2 interaction with formation oil. Future research should focus on evaluating the impact of different types of crude oil (such as light crude oil, heavy crude oil, etc.) on MMP, and how these differences affect the efficiency of CO_2 flooding.

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