

Article

Experimental Investigation on Pore-Permeability Evolution of Tight Carbonate Rocks in SC-CO₂ Acidizing

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Abstract

The Lower Paleozoic carbonate reservoirs in the Yan'an Gas Field are characterized by low porosity, low permeability, and strong heterogeneity, which make effective stimulation difficult. Although supercritical CO₂ (SC-CO₂) acidizing has shown promising results in field applications, the effects of SC-CO₂ concentration and acid type on the pore structure evolution of tight carbonate rocks remain poorly understood. In this study, matrix acidizing experiments were conducted using SC-CO₂+acid multi-component fluids, and nuclear magnetic resonance (NMR) together with porosity–permeability measurements were employed to characterize the changes in pore structure before and after acidizing. The results indicate that compared with a single acid injection, SC-CO₂+acid combined acidizing significantly improves core porosity and permeability. It promotes the dissolution and expansion of small and medium pores, enhances the connectivity of isolated pores, and increases the proportion of medium and large pores along with pore connectivity. SC-CO₂ concentration is a key influencing factor: higher concentrations result in stronger dissolution and greater improvements in porosity and permeability. The acidizing effect of gelled acid mixed with SC-CO₂ is superior to that of regular acid, attributed to the higher viscosity of gelled acid, which prolongs the acid–rock reaction time, enabling more uniform and sufficient dissolution and thus more significant improvements in pore structure and acid flow capacity. This research provides valuable guidance for the design of SC-CO₂ acidizing treatments in carbonate reservoirs.

Keywords: carbonate rocks; SC-CO₂; matrix acidizing; porosity; permeability

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1. Introduction

The Yan'an Gas Field is located in the southeastern part of the Ordos Basin, China (Figure 1), the Lower Paleozoic carbonate reservoirs in the Yan'an Gas Field are low-porosity (0.6~4.5%) and low-permeability (<0.1 mD) reservoirs, with high reservoir temperatures (90~120 °C), high closure pressures (50~70 MPa), and low pressure coefficients (0.7~0.9), posing significant challenges to stimulation [1,2]. Table 1 compares the reservoir properties of the Majiagou Formation in the study area with those of other representative tight carbonate gas reservoirs in China. As shown in Table 1, the Majiagou carbonates of the Yan'an Gas Field are comparable to or tighter than these reservoirs, which underscores the difficulty of effective stimulation.

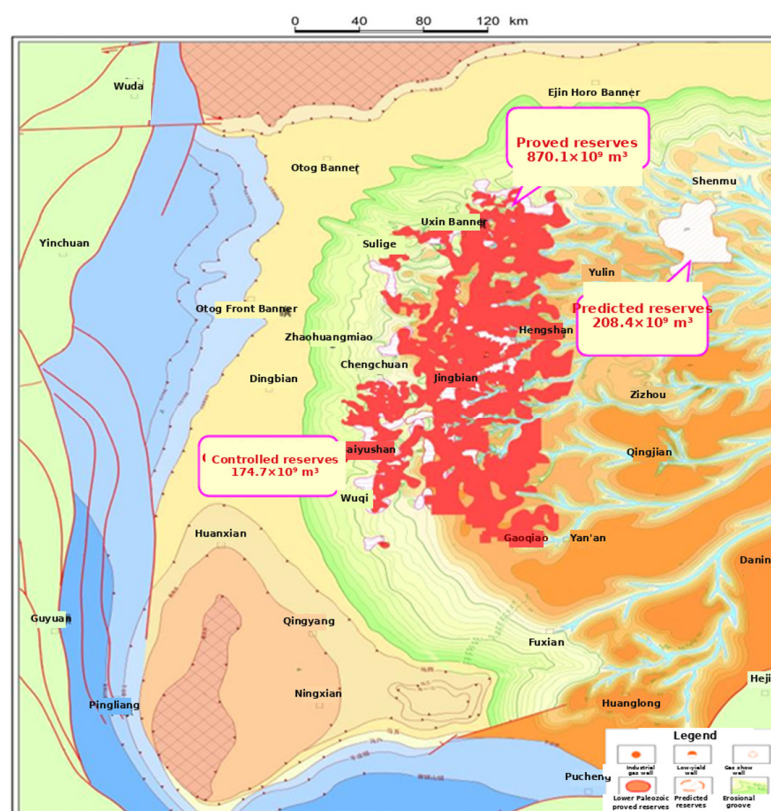


Figure 1. Schematic location map of the Yan'an Gas Field, Ordos Basin, China.

Table 1. Comparison of reservoir properties between the Yan'an Gas Field and other representative tight carbonate gas reservoirs in China.

Gas Field (Basin)	Formation	Porosity, %	Permeability, mD	Distinctive Features
Yan'an Gas Field (Ordos Basin)	Ordovician Majiagou	0.6–4.5	<0.1	High temperature (90–120 °C), high closure pressure (50–70 MPa), low pressure coefficient
South-central Ordos Basin [3]	Ordovician Majiagou	0.4–5.26	0.011–0.059	Tight dolomite, strong heterogeneity
Southern Tahe Oilfield (Tarim Basin) [4]	Ordovician	0.6–3.8	0.02–21.02	Ultra-deep (>6000 m), fracture-cavity type
Longwangmiao Gas Field (Sichuan Basin) [5]	Cambrian Longwangmiao	0.2–11.8	0.001–10	Deep dolomite, strong heterogeneity

In recent years, CO₂-based reservoir stimulation technology has attracted growing interest due to its potential to enhance oil and gas production [6,7]. With low viscosity, high density, and high diffusivity, supercritical/liquid CO₂ can rapidly penetrate micro-pores and micro-fractures. CO₂ fracturing reduces breakdown pressure, creates complex fracture networks, energizes the formation, improves flowback, and minimizes reservoir damage, thereby enhancing single-well production in an efficient and environmentally friendly manner [8]. As the wellbore temperature decreases, the CO₂ density increases and the flow velocity decreases; consequently, the wellhead pressure declines in sync with the bottomhole temperature [9]. In CO₂+acid fracturing of carbonate reservoirs, SC-CO₂ reduces acid leak-off, improves fracture etching efficiency, forms large-volume, high-conductivity acid-etched fractures, and significantly enhances reservoir productivity [10,11]. Additionally, substituting CO₂ for part of the liquid working fluid reduces water consumption

during operations. SC-CO₂ can also transport acid to areas inaccessible by regular acid fracturing, expanding the effective stimulation range. During flowback, the rapid pressure drop induces phase change of SC-CO₂ in fractures, which vaporizes into gas, generating substantial energy and greatly improving flowback efficiency [12]. Moreover, CO₂-based reservoir stimulation is consistent with carbon capture, utilization, and storage (CCUS) strategies: part of the injected CO₂ can be retained in the reservoir, coupling enhanced gas recovery with geological carbon storage [13,14]. The current progress of CO₂ injection for enhanced recovery and carbon storage has been reviewed by Jia et al. [15].

Currently, SC-CO₂ stimulation technology has been field-applied in carbonate reservoirs with promising production enhancement results. In a pilot well in Saudi Arabia's acid-bearing carbonate reservoir, CO₂ acid fracturing increased production by 2.5 times compared to pre-fracturing levels, with single-well production reaching twice that of adjacent wells [11]. In the Jurassic gas reservoir in northern Kuwait, CO₂ acid fracturing shortened acid flowback time, supplemented reservoir energy, and improved single-well production [12].

Numerous scholars have investigated the reaction mechanism of SC-CO₂ in matrix acidizing. Cheng et al. (2016) [16] observed through core experiments that CO₂ generated during matrix acidizing exists in dissolved and free states. At low pressures, gaseous CO₂ increases wormhole diameter, while at high pressures, SC-CO₂ completely dissolves in the acid, exerting no significant effect on wormhole propagation. Yan et al. (2019) [17] demonstrated that in situ generated CO₂ forms stable SC-CO₂ foamed fluid at formation pressures exceeding 8.0 MPa and temperatures exceeding 60 °C, which exhibits diverting effects during core displacement, improving matrix acidizing efficiency. Kartini et al. (2021) [18] observed that the acid-etched wormholes formed by mixing free SC-CO₂ with acid are slender and characterized by expanded dissolution pores. Alarji et al. (2022) [19] observed that gaseous CO₂, as a reaction product, has no obvious impact on wormhole growth during matrix acidizing but increases fluid flow resistance. However, most of these studies focused on the phase state of CO₂ and on wormhole propagation behavior, while systematic experimental evidence on how SC-CO₂ concentration and acid type govern the pore structure evolution of tight carbonate rocks remains scarce [20]. Related experimental and review studies on SC-CO₂ stimulation of tight and unconventional reservoirs likewise indicate that the controlling factors and field-scale applicability of this technology are not yet fully understood [21,22].

To address these gaps, this study conducts matrix acidizing experiments on tight carbonate cores from the Majiagou Formation using SC-CO₂+acid multi-component fluids. The objectives are threefold: (1) to compare the pore-permeability evolution induced by SC-CO₂+acid combined acidizing with that of a single regular acid injection; (2) to quantify the effect of SC-CO₂ concentration on acidizing performance; and (3) to evaluate the influence of acid type (regular acid versus gelled acid) on pore structure changes. The findings provide technical guidance for the application of CO₂ acid fracturing in tight carbonate reservoirs.

2. Experimental Methodology

2.1. Materials

Core samples were collected from outcrops of the Ordovician Majiagou Formation carbonate rocks, with dolomite content exceeding 90%, and minor amounts of calcite, quartz, and clay minerals (Figure 2). The average porosity of the core samples was 3.0% (Figure 3), and the average permeability was 0.015 mD (Figure 4). The NMR curves of the cores in their initial state showed minimal differences, resulting in negligible impacts on experimental results (Figure 5). It should be noted that the mineral composition of

the samples varies to some extent: Samples 1, 8, 9, and 12 contain a higher proportion of calcite than the other dolomite-dominated samples (Figure 2), and this mineralogical variability may contribute to the differences in acidizing response discussed below. The outcrop rock samples have an average dynamic Young's modulus of 100.6 GPa and an average dynamic Poisson's ratio of 0.301; the outcrop cores have an average static Young's modulus of 70.7 GPa and an average static Poisson's ratio of 0.283.

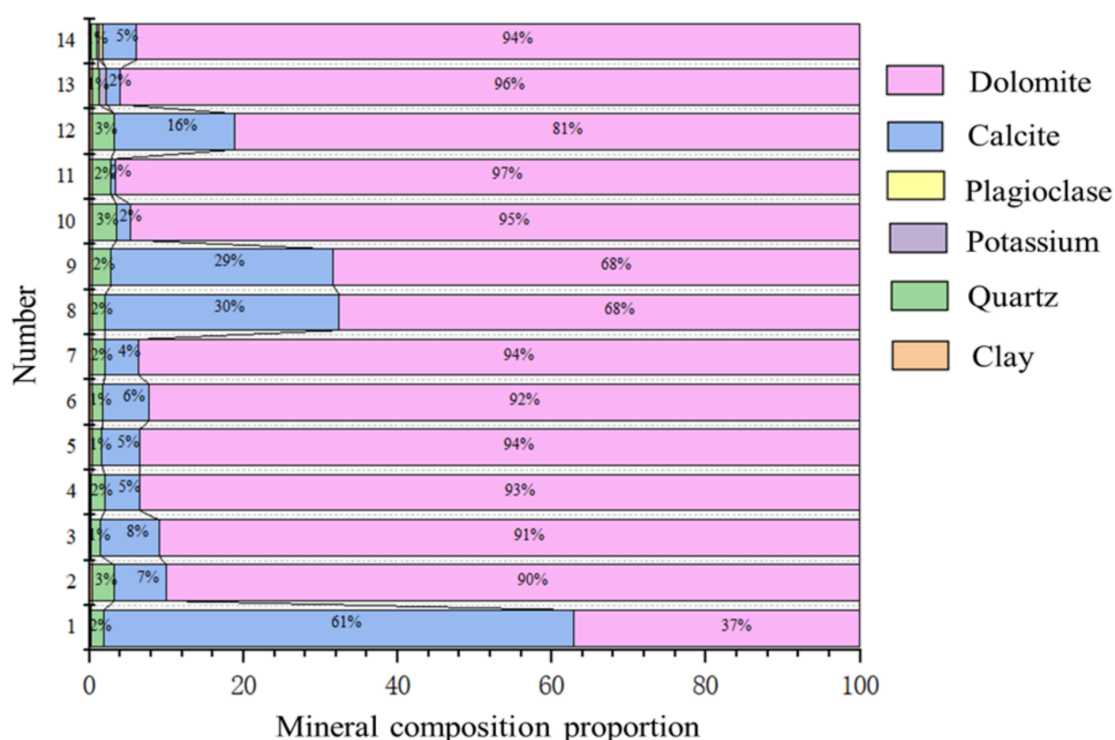


Figure 2. Mineral composition.

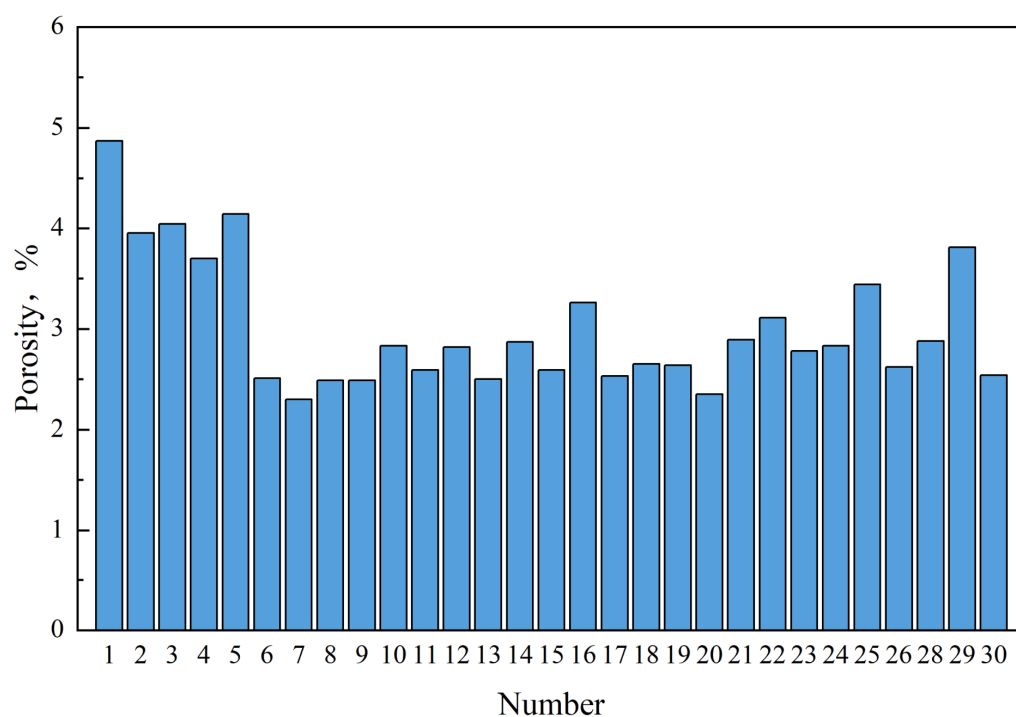


Figure 3. Porosity parameters.

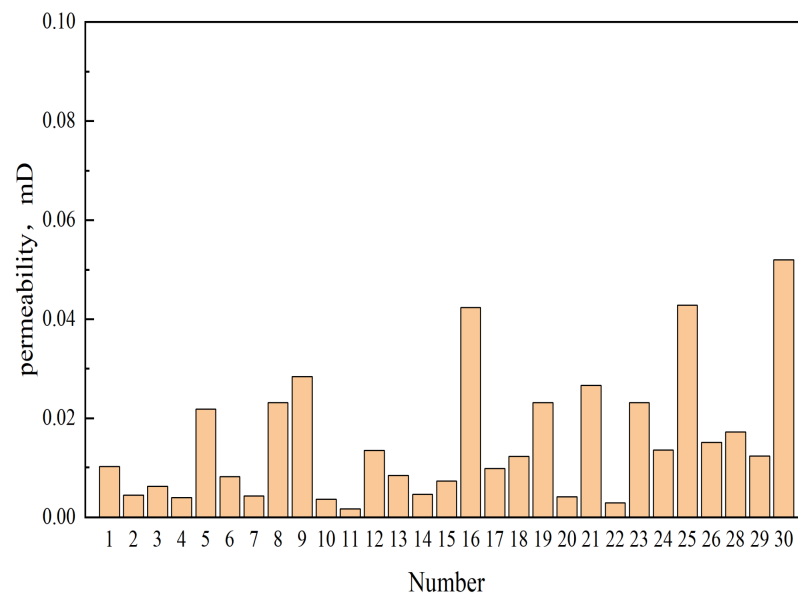


Figure 4. Permeability parameters.

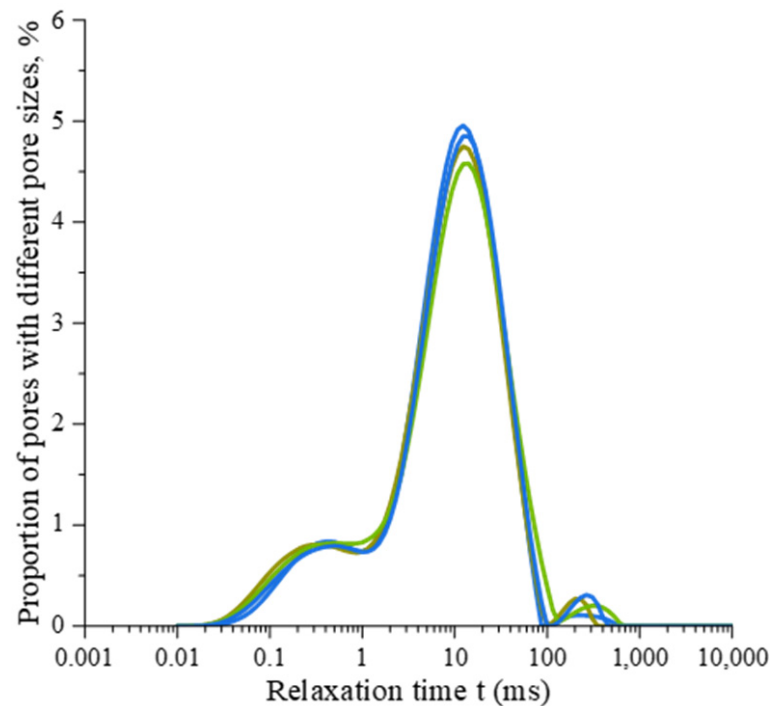


Figure 5. NMR curves of cores before acidizing.

Two acid systems were selected for the experiments: gelled acid and regular acid, with formulations and viscosity in Table 2.

Table 2. Formulations of acid systems used in experiments.

Acid System	Formulation	Viscosity at 25 °C (mPa·s)
Gelled Acid	20% HCl + 1.5% Corrosion Inhibitor + 0.15% Citric Acid + 0.55% Gelling Agent	16
Regular Acid	20% HCl + 1.5% Corrosion Inhibitor + 0.15% Citric Acid	1.2

2.2. Experimental Method

2.2.1. Experimental Device and Procedure

Two types of experiments were conducted: SC-CO₂ matrix acidizing experiments and core porosity–permeability testing. The SC-CO₂ matrix acidizing experiments were performed using an SC-CO₂ and acid mixing device (Figure 6a), and SC-CO₂ acidizing experimental setup (Figure 6b). The core porosity–permeability testing system consisted of an NMR device (Figure 6c) and a porosity–permeability testing device (Figure 6d).



Figure 6. Experimental device. (a) CO₂ and acid mixing device; (b) SC-CO₂ acidizing device; (c) core NMR testing device; (d) porosity–permeability testing device.

The experimental procedure is illustrated in Figure 7. The core porosity and permeability before acidizing were first measured using a porosity–permeability testing device. Subsequently, the pore structure of the core prior to acidizing was characterized via nuclear magnetic resonance (NMR). Then, an SC-CO₂ acidizing device was employed to simulate the flow and reaction processes of SC-CO₂+acid multi-component fluids in the rock matrix under reservoir conditions. Finally, the porosity and permeability of the core after acidizing were determined with the same porosity–permeability testing device, and the post-acidizing pore structure was obtained by NMR. This work reveals the variations in core porosity and permeability during SC-CO₂ matrix acidizing. The detailed procedures are as follows:

1. The core samples were cleaned thoroughly and dried to constant weight.
2. The length and diameter of the core samples were measured, and their weights were weighed accurately.
3. The core samples were placed into the porosity–permeability testing apparatus to determine their porosity and permeability before acidizing.

4. The pore structure of the core samples prior to acidizing was characterized using nuclear magnetic resonance (NMR).
5. The core samples were installed in the SC-CO₂+acid multi-component displacement device, and the matrix acidizing experiment was initiated subsequently.
6. The acidized core samples were cleaned thoroughly and dried to constant weight.
7. The length, diameter and weight of the acidized core samples were measured and weighed again.
8. The acidized core samples were placed into the porosity–permeability testing apparatus to test their porosity and permeability; the porosity and permeability change rates of the core samples before and after acidizing were calculated, with the calculation methods shown in Equations (1) and (2).
9. Finally, the pore structure of the acidized core samples was obtained via nuclear magnetic resonance (NMR).

$$\omega_K = \frac{K_a - K_b}{K_b} \times 100\% \quad (1)$$

$$\omega_\varphi = \frac{\varphi_a - \varphi_b}{\varphi_b} \times 100\% \quad (2)$$

where ω_K is core permeability improvement rate, %; K_a is core permeability after acidizing, mD; K_b is core permeability before acidizing, mD; ω_φ is core porosity improvement rate, %; φ_a is core porosity after acidizing, %; and φ_b is core porosity before acidizing, %.

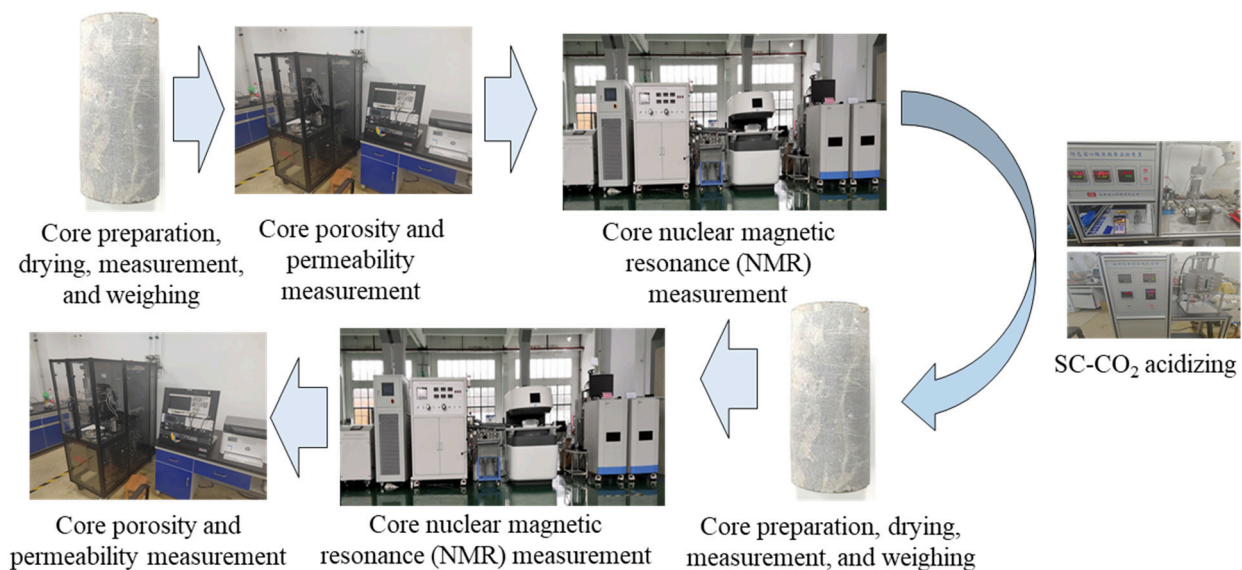


Figure 7. Main experimental flow chart.

2.2.2. Experimental Parameter Determination

The pumping rate in field operations is 2~3 m³/min. Simulation results indicate a total fracture volume of 93.6 m³, a total fracture length of 278 m, and an average fracture width of 4 mm. Taking the average pumping rate of 2.5 m³/min, as shown in Equation (3), converting it using the contact ratio formula, the corresponding experimental injection rate is 0.52 mL/min; therefore, 0.5 mL/min was adopted in the experiments.

$$\frac{Q_f}{A_f} = \frac{Q_l}{A_l} \quad (3)$$

where Q_f is the field pumping rate, m^3/min ; A_f is the fracture area, m^2 ; Q_i is the experimental injection rate, mL/min ; and A_i is the cross-sectional area of the core, m^2 .

The geothermal gradient in the study area is $2.46\sim 3.18\text{ }^\circ\text{C}/100\text{ m}$ (average $2.8\text{ }^\circ\text{C}/100\text{ m}$), and the Majiagou Formation reservoir is buried at depths of $2500\sim 4000\text{ m}$, corresponding to reservoir temperatures of $70\sim 110\text{ }^\circ\text{C}$. The experimental temperature was therefore set to $90\text{ }^\circ\text{C}$, the average reservoir temperature.

Logging data from this block indicate an average rock density of $2.71\text{ g}/\text{cm}^3$. The reservoir pressure coefficient ranges from 0.8 to 0.9, with an average of 0.82. The average overburden stress is 60 MPa and the average pore pressure is 20 MPa; as shown in Equation (4), according to the effective stress theory, the average effective stress is 40 MPa. Therefore, the confining pressure in the experiments was set to 40 MPa.

$$\sigma_c = \sigma_v - \alpha P_p \quad (4)$$

where σ_c is effective stress, MPa; σ_v is overburden stress, MPa; α is Biot coefficient, dimensionless; and P_p is pore pressure, MPa.

2.3. Experimental Schedule

In order to investigate the effects of SC-CO₂ concentration and acid type on porosity and permeability improvement throughout matrix acidizing, experimental parameters including reaction temperature, back pressure, acid injection rate, and total acid injection time were kept constant. The experimental temperature was $90\text{ }^\circ\text{C}$, acid injection rate was $0.5\text{ mL}/\text{min}$, total injection time was 30 min, and confining back pressure was 40 MPa. Both acid systems were based on 20% HCl. The specific experimental scheme is shown in Table 3.

Table 3. Acidizing experiments scheme.

No.	Acid System	Back Pressure, MPa	Injection Rate, mL/min	Temperature, $^\circ\text{C}$	Injection Time, min
1	Regular acid + 10%SC-CO ₂	40	0.5	90	30
2	Regular acid + 5%SC-CO ₂				
3	Gelled acid + 10%SC-CO ₂				
4	Regular acid				

Experiments 1 and 4 investigate the effect of SC-CO₂ acidizing on porosity and permeability, experiments 1 and 2 investigate the influence of SC-CO₂ concentration, and experiments 1 and 3 investigate the effect of acid type. Due to the limited availability of outcrop cores with comparable initial properties, one core was used for each experimental condition in this study. This single-specimen design does not allow a statistical error analysis, which is a limitation of the present work; replicate experiments will be conducted in future studies to quantify the experimental uncertainty.

3. Results and Discussion

3.1. Characteristics of SC-CO₂ Matrix Acidizing

Compared with a single regular acid injection, the combination of SC-CO₂ and acid significantly improved core porosity and permeability. After regular acidizing, the core permeability increased from $2.66 \times 10^{-2}\text{ mD}$ to $3.71 \times 10^{-2}\text{ mD}$, representing a 39% improvement. In contrast, after acidizing with regular acid + 10% SC-CO₂, the permeability increased from $1.22 \times 10^{-2}\text{ mD}$ to $2.56 \times 10^{-2}\text{ mD}$, a remarkable 110% improvement (Figure 8a). For porosity, regular acidizing led to an increase from 2.89% to 3.48% (20%

improvement), while regular acid + 10% SC-CO₂ acidizing increased porosity from 2.65% to 4.36% (65% improvement) (Figure 8b).

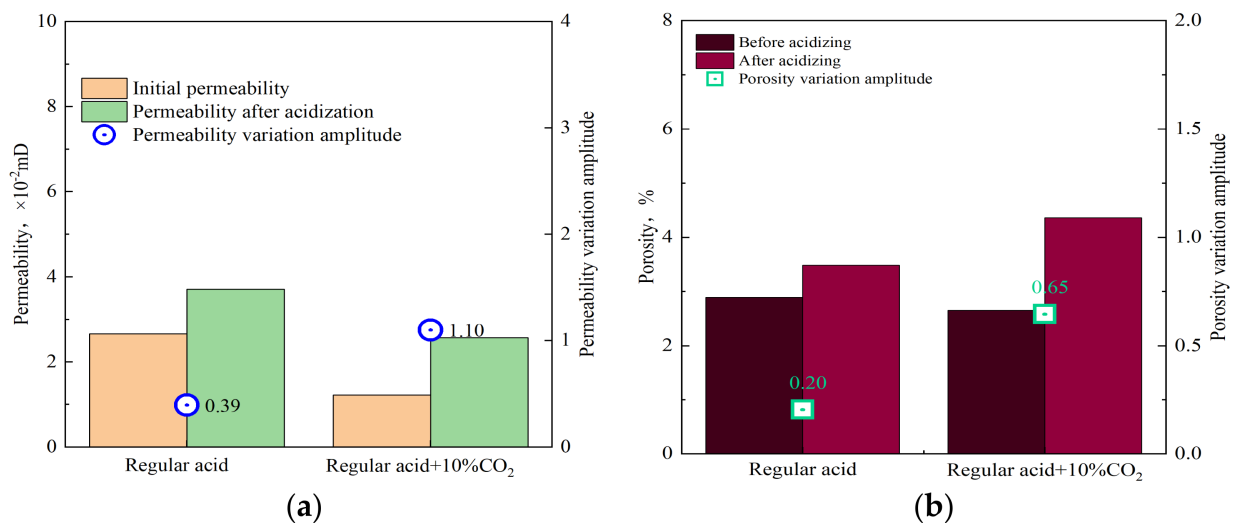


Figure 8. Comparison of porosity–permeability between single-acid injection and SC-CO₂+acid combined acidizing. (a) Permeability variation of low-permeability core; (b) porosity variation of low-permeability core.

Figure 9 presents the NMR T spectra of cores after regular acidizing and regular acid + 10% SC-CO₂ acidizing. The T value is positively correlated with pore size: smaller T values indicate smaller pores, and vice versa. As shown in Figure 9a, after regular acidizing, the T spectrum peak shifted mainly to the medium T interval (10 ms < T < 100 ms), indicating that some small pores (T < 10 ms) were dissolved and expanded into medium pores, increasing the proportion of medium pores. Additionally, some medium pores were further dissolved into small large pores (T > 100 ms), but the improvement in large pore proportion was limited. In contrast, Figure 9b shows that the T spectrum after regular acid + 10% SC-CO₂ acidizing exhibited a multi-peak distribution. On one hand, a distinct small-pore peak appeared, suggesting the formation of new micro-pores during acidizing. On the other hand, the intensity of T peaks corresponding to medium and large pores increased significantly, indicating extensive dissolution and expansion of small and medium pores. Moreover, the results indicate that SC-CO₂ enlarges the pore diameter of the core samples.

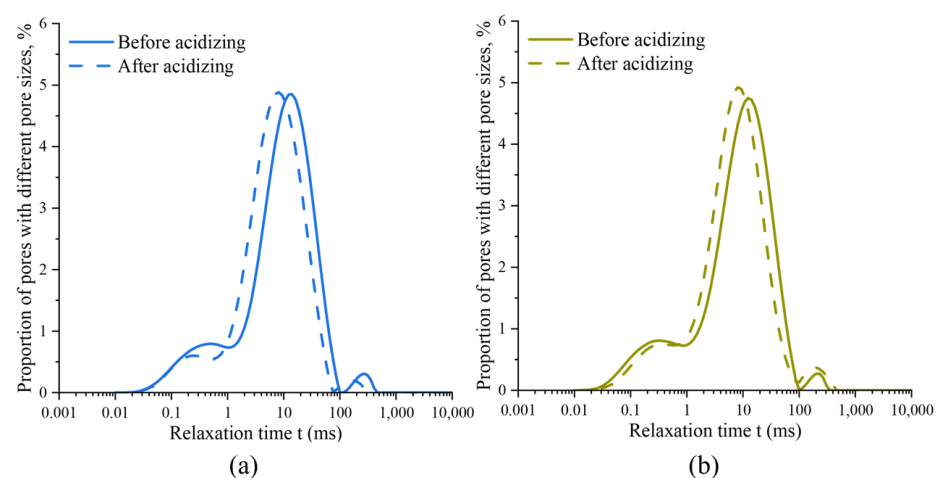


Figure 9. Comparison of pore structure between single-acid injection and SC-CO₂+acid combined acidizing. (a) Regular acid; (b) regular acid+10%SC-CO₂.

3.2. Effecting Factors of SC-CO₂ Matrix Acidizing

3.2.1. Effect of SC-CO₂ Concentration

Figure 10 compares the changes in core porosity and permeability after acidizing with regular acid mixed with different SC-CO₂ concentrations (5% and 10%). As shown in Figure 10a, regular acid + 5% SC-CO₂ acidizing increased permeability from 1.34×10^{-2} mD to 1.89×10^{-2} mD (41% improvement), while regular acid + 10% SC-CO₂ acidizing achieved a 110% permeability improvement, significantly higher than that of the 5% SC-CO₂ concentration. For porosity (Figure 10b), regular acid + 5% SC-CO₂ acidizing increased porosity from 2.82% to 3.54% (26% improvement), whereas regular acid + 10% SC-CO₂ acidizing resulted in a 65% porosity improvement. These results indicate that the acidizing effect is significantly enhanced with increasing SC-CO₂ concentration.

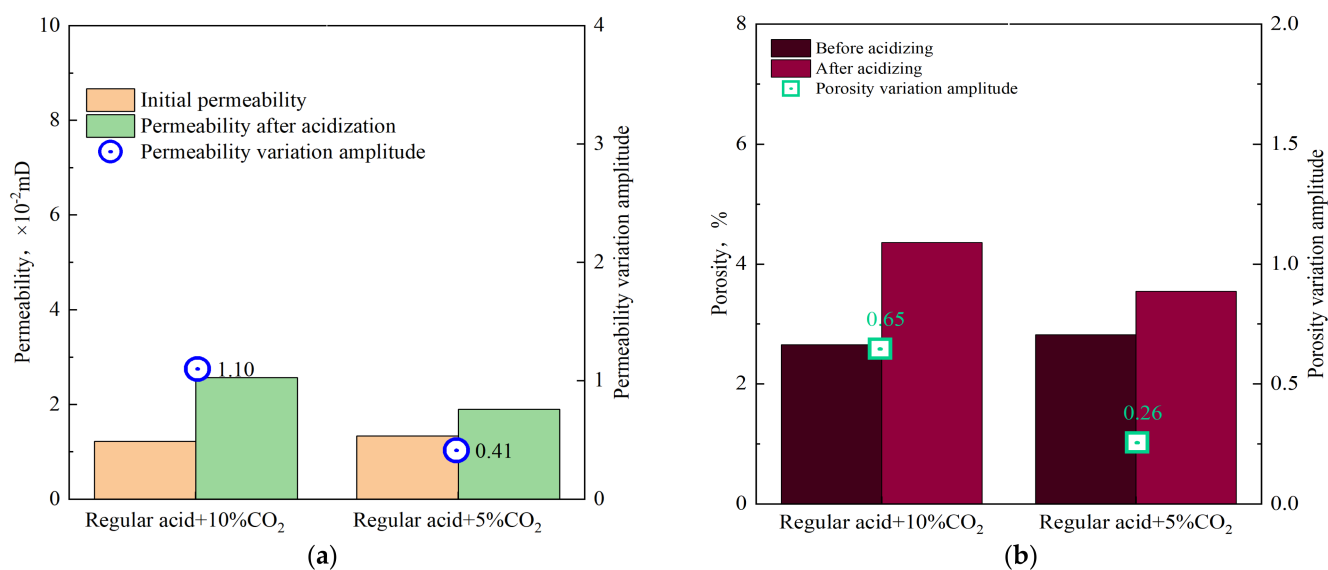


Figure 10. Effect of SC-CO₂ concentration on porosity and permeability. (a) Permeability variation of low-permeability core; (b) porosity variation of low-permeability core.

Figure 11 shows the NMR T spectra of cores after acidizing with different SC-CO₂ concentrations. As shown in Figure 11a, after regular acid + 5% SC-CO₂ acidizing, the T spectrum peaks were mainly concentrated in the small and medium pore intervals, with a significant increase in the proportion of small pores. Some small and medium pores were dissolved into smaller medium and large pores, but the improvement in large pore proportion was insignificant, indicating that low-concentration SC-CO₂ has limited dissolution effect and tends to form small pores. In contrast, Figure 11b shows that after regular acid + 10% SC-CO₂ acidizing, the T spectrum peaks shifted significantly to the medium and large pore intervals, with a substantial increase in the intensity of peaks corresponding to medium and large pores. This suggests that high-concentration SC-CO₂ forms a stronger synergistic dissolution effect with acid, not only dissolving small and medium pores but also further expanding large pores and effectively connecting isolated pores, thereby significantly improving pore connectivity and achieving substantial enhancements in porosity and permeability.

In summary, SC-CO₂ concentration is a key factor influencing matrix acidizing performance. Lower concentrations result in poor pore expansion and permeability enhancement, with a tendency to form small pores. As SC-CO₂ concentration increases, the synergistic dissolution effect with acid is strengthened, leading to deeper pore dissolution, improved pore connectivity, and greater improvements in porosity and permeability. It should be noted that only two SC-CO₂ concentrations (5% and 10%) were tested in this study, so 10%

cannot yet be regarded as the optimum concentration. The optimum value is expected to depend on the balance between the enhanced dissolution provided by SC-CO₂ and the reduced acid volume fraction, as well as on field operational constraints such as pumping pressure and CO₂ supply.

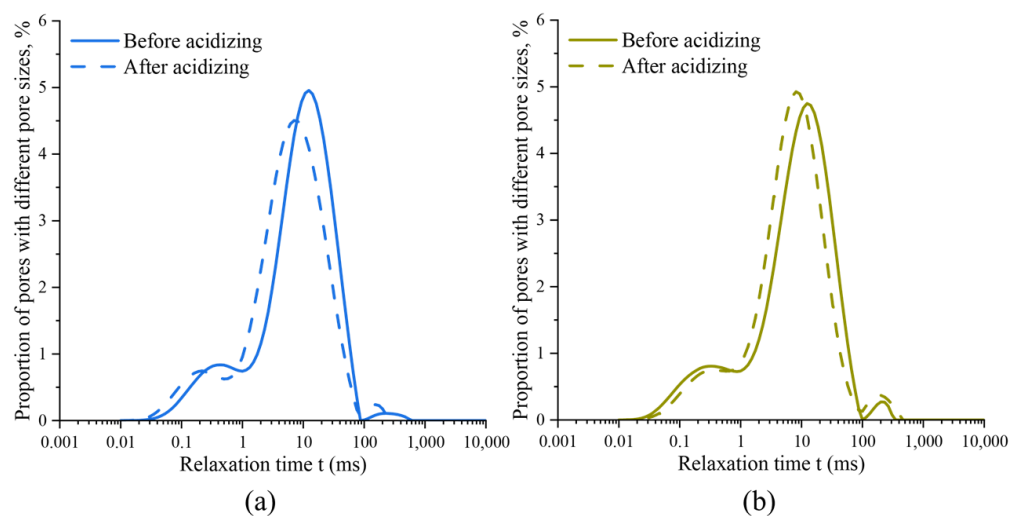


Figure 11. Effect of SC-CO₂ concentration on pore structure. (a) Regular acid + 5%SC-CO₂; (b) regular acid + 10%SC-CO₂.

3.2.2. Effect of Acid Type

Figure 12 compares the changes in core porosity and permeability after acidizing with 10% SC-CO₂ mixed with different acid types (regular acid and gelled acid). As shown in Figure 12a, regular acid + 10% SC-CO₂ acidizing achieved a 110% permeability improvement, while gelled acid + 10% SC-CO₂ acidizing increased permeability from 4.28×10^{-2} to 9.60×10^{-2} mD (124% improvement), outperforming the regular acid system. For porosity (Figure 12b), regular acid + 10% SC-CO₂ acidizing led to a 65% improvement, whereas gelled acid + 10% SC-CO₂ acidizing increased porosity from 3.44% to 6.14% (78% improvement), demonstrating more significant porosity–permeability improvements.

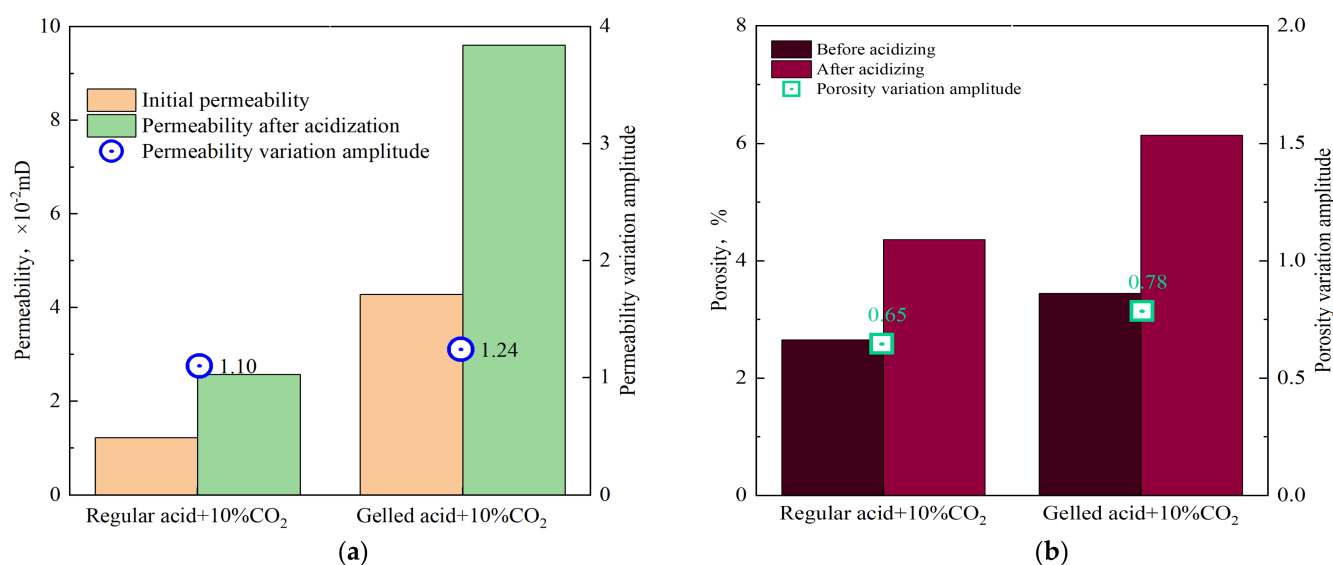


Figure 12. Effect of acid type on porosity and permeability. (a) Permeability variation of low-permeability core; (b) porosity variation of low-permeability core.

Figure 13 presents the NMR T spectra of cores after acidizing with 10% SC-CO₂ mixed with different acid types. As shown in Figure 13a, regular acid + 10% SC-CO₂ acidizing resulted in obvious dissolution of small, medium, and large pores, with a significant increase in the proportion of medium and large pores and improved pore connectivity. In contrast, Figure 13b shows that after gelled acid + 10% SC-CO₂ acidizing, the T spectrum peaks were mainly concentrated in the medium pore interval, with a substantial increase in medium pore proportion and a noticeable decrease in small pore proportion. The dissolution of medium and large pores was relatively mild. This phenomenon is primarily attributed to the higher viscosity and stronger retarding capacity of gelled acid compared to regular acid, which prolongs the acid–rock reaction time and enables more uniform and sufficient dissolution.

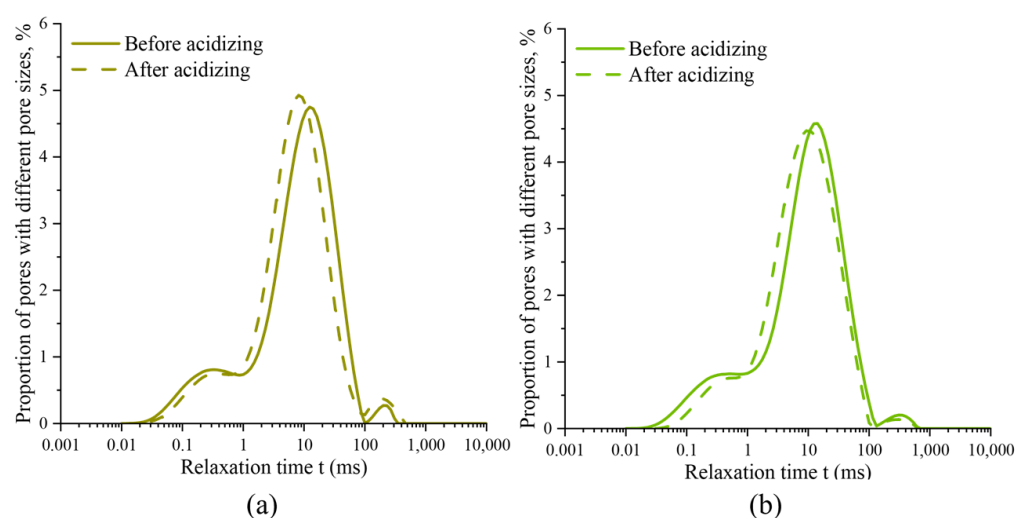


Figure 13. Effect of acid type on pore structure. (a) Regular acid + 10%SC-CO₂; (b) gelled acid + 10%SC-CO₂.

Comparing the acidizing performance of the two acid systems, gelled acid exhibits superior capacity to improve matrix porosity and permeability compared to regular acid. The pore size distributions of cores after acidizing with different acid types mixed with SC-CO₂ are relatively similar, dominated by medium and large pores. However, gelled acid results in a higher proportion of medium pores and a more uniform pore structure.

3.3. Practical Limitations and Field-Scale Implications

The experimental results obtained at the core scale provide mechanistic insights, but several factors must be considered when transferring them to field-scale treatments. First, core-scale experiments cannot capture reservoir heterogeneity, natural fractures, or the in situ stress state; the improvement rates observed in this study should therefore be regarded as upper-bound indicators rather than direct predictions of well performance. Second, the field cases in Saudi Arabia and Kuwait demonstrate the feasibility of CO₂-based acid fracturing at the well scale [11,12], suggesting that the laboratory trends identified here are directionally consistent with field observations. Nevertheless, pilot field tests in the Yan'an Gas Field are required to validate the laboratory conclusions under real reservoir conditions.

SC-CO₂ acidizing also has economic, operational, technical, and environmental disadvantages that must be weighed against its benefits. Economically, CO₂ supply, transportation, and high-pressure injection equipment increase the upfront cost relative to conventional acidizing, although partial savings may arise from reduced water consumption and improved flowback efficiency. Operationally, maintaining CO₂ in a supercritical

state requires strict control of wellhead pressure and temperature, and the strong cooling associated with CO₂ injection may cause low-temperature damage to tubulars and wellhead equipment. Technically, the low viscosity of SC-CO₂ can lead to early acid breakthrough in heterogeneous formations, and corrosion control is more demanding in the presence of carbonic acid. Environmentally, although part of the injected CO₂ remains in the reservoir, incomplete retention leads to CO₂ emissions during flowback; integrating the treatment with carbon capture, utilization, and storage (CCUS) schemes can mitigate this concern [13,14].

4. Conclusions

This study investigates the SC-CO₂ matrix acidizing effect of carbonate rocks through comprehensive analysis of core porosity–permeability improvements and pore structure changes. The main conclusions are as follows:

1. SC-CO₂+acid combined matrix acidizing achieves better porosity and permeability improvements than single-acid regular acidizing. Compared with regular acidizing, the addition of SC-CO₂ to acid promotes the dissolution of small pores, increases the proportion of medium pores, and enhances the proportion of large pores.
2. Lower SC-CO₂ concentrations lead to poor pore expansion and permeability enhancement, with a tendency to form small pores. As SC-CO₂ concentration increases, the acidizing effect is significantly strengthened.
3. Gelled acid exhibits superior capacity to improve matrix porosity and permeability compared to regular acid. The effects of gelled acid and regular acid mixed with SC-CO₂ on core pore size distribution are relatively similar, with both systems favoring the development of medium and large pores.

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Data Availability Statement: We confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: Author C.L., J.L., Y.G. and Q.H. were employed by the company Shaanxi Yanchang Petroleum (Group) Co., Ltd., Natural Gas Research Institute Branch. The authors declare that this study received funding from Shaanxi Provincial Key Research and Development Program (2025CY-YBXM-612). The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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