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Research Article

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Experimental Study on Acidizing Parameter Optimization and Reservoir Adaptability of a Multi-Component Organic Solid Retarded Acid System for High-Temperature Carbonate Reservoirs

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Abstract

To address the challenges of short effective treatment distance and limited stimulation period in conventional acidizing of high-temperature carbonate reservoirs, this study focuses on a multi-component organic solid retarded acid system with superior retarding performance. Utilizing high-temperature/high-pressure (HTHP) simulation and high-precision core CT scanning technology, the effects of injection rate, acid concentration, reservoir temperature, and rock permeability on acidizing performance were systematically investigated.The results indicate that at 140 °C, the optimal injection rate for a 15% acid concentration is 1~2 mL/min. At this rate, the acid-rock system achieves mass transfer-reaction equilibrium, forming a single penetrating dominant wormhole, while the pore volume to breakthrough (PVBT) is reduced by more than 30% compared to conventional acids. A concentration range of 15%~20% is identified as suitable for high-temperature conditions, characterized by fewer wormhole branches and stronger adaptability to varying rates. As temperature increases, the optimal injection rate shifts toward higher values; however, the impact of temperature on acidizing effectiveness is significantly less than that of the injection rate. Compared to high-permeability cores, this system more readily forms slender dominant wormholes in low-permeability cores, with the breakthrough volume decreasing by approximately 40%, demonstrating excellent reservoir adaptability.This study defines the optimal technical parameters for multi-component organic solid retarded acid and reveals the development patterns of acid-etched wormholes under high-temperature conditions. These findings provide a theoretical basis and parameter support for the field application of acidizing in high-temperature carbonate reservoirs, offering significant engineering value for enhancing oil and gas production.

Keywords: rganic solid retarded acid; High-temperature carbonate reservoir; Acidizing parameter optimization; Acid-etched wormhole; Reservoir adaptability; High-temperature and high-pressure (HTHP) experiment; 3D CT imaging

1. Introduction

Carbonate reservoirs represent one of the core reservoir types for global oil and gas exploration and development, accounting for over 60% of the world's total oil and gas reserves and more than 50% of global production, occupying an irreplaceable position in the industry(Bentley 2002; Haider). As exploration and development advance into deep and ultra-deep formations, high-temperature (140 °C) tight and low-permeability carbonate reservoirs have become critical targets. Characterized by great burial depth, high geothermal gradients, narrow pore throats, and strong heterogeneity, these reservoirs often exhibit poor physical properties and low productivity. Consequently, acidizing stimulation has become a key technical means to achieve enhanced production and efficiency (Al Rbeawi et al. 2018).

The core of acidizing stimulation is the chemical reaction between the acid and the carbonate rock to form acid-etched wormholes, which connect the reservoir's primary pores and fractures to enhance permeability(Guo et al. 2020; Dong 2021). The morphology and penetration distance of these wormholes directly determine the effectiveness of the treatment (Buijse 2000; Qi et al. 2019). However, conventional liquid acid systems (such as hydrochloric acid and mud acid) face challenges under high-temperature conditions, including excessive reaction rates, short effective penetration distances, and severe surface dissolution(Van Hong and Ben Mahmud 2017; Alhamad et al. 2020; Li et al. 2024a). these issues lead to poor wormhole development and short effective stimulation periods, making it difficult to meet the requirements for high-temperature carbonate reservoirs (Mahmoud and Nasr-El-Din 2014; Xu et al. 2020; Monette and Nguyen 2023). As a novel retarded system, the multi-component organic solid acid system achieves retardation by controlling H^+ ionization (with an initial pH range of 2~3). It offers advantages such as ease of transport and storage, low volatility, controllable reaction rates, excellent high-temperature resistance, long effective penetration distance, and low environmental impact. By slowly releasing H+ through ionization, its activity can be regulated to effectively avoid surface dissolution and rapid reaction at high temperatures, making it a preferred system for stimulating high-temperature carbonate formations (Al-Harthy et al.).

Currently, research on multi-component solid retarded acid systems both domestically and internationally has primarily focused on system preparation, retardation performance evaluation, and the impact of single factors on acidizing effects([CSL STYLE ERROR: reference with no printed form.]). Systematic optimization of acidizing process parameters under high-temperature conditions remains limited(Ma et al. 2018; Zhao et al. 2024; Aboud et al.). Furthermore, research on reservoir adaptability under the coupling of multiple factors—such as acid concentration, reservoir temperature, and rock permeability—is still insufficient(Li et al. 2024b; Wu et al. 2025). In particular, there is a lack of in-depth discussion on the development laws and formation mechanisms of acid-etched wormholes at 140 °C(Shi and Lai 2026; Bale et al.). Additionally, existing studies often rely on single indicators to evaluate acidizing performance, which fails to comprehensively and accurately reflect the compatibility between the acid and the reservoir(Dargi et al. 2023). Therefore, it is urgent to establish a multi-dimensional, multi-indicator evaluation system ([CSL STYLE ERROR: reference with no printed form.]).

In view of this, this study focuses on tight and low-permeability carbonate reservoirs at 140 °C. Core acidizing flow experiments were conducted using an HTHP acidizing simulation apparatus, combined with high-precision full-core CT scanning and Avizo 3D reconstruction technology. First, the injection rate for the multi-component organic solid retarded acid system was optimized at 140 °C. Subsequently, the effects of acid concentration (5%, 15%, 20%), reservoir temperature (90 °C, 140 °C), and rock permeability (high and low) on etching morphology, pressure differential dynamics, pore volume to breakthrough (PVBT), and the 3D morphology of wormholes were systematically investigated. This work reveals the development mechanisms of wormholes under multi-factor coupling, clarifies the reservoir adaptability of the organic solid acid system, and establishes an optimized technical parameter framework. The results of this study fill the gap in multi-factor coupling research for high-performance organic solid retarded acids under high temperatures, providing a critical theoretical basis

and process guidance for field operations in high-temperature carbonate reservoirs, with significant theoretical and engineering value.

2、Experimental Materials and Methods

2.1 Experimental Materials

Table 1. Experimental Materials

Experimental Materials	Key Parameters and Performance Indicators	Pretreatment and Applications
Carbonate Core Samples	Natural cylindrical plugs, ϕ25 mm×50 mm; High-permeability type: 50~100 mD; Low-permeability type: 1~5 mD	Dried, polished, and cleaned; used to measure changes in porosity and permeability.
Multi-component Organic Solid Acid	Mass concentration: 5%,15%,20%; pH value: 1.5~2.0; Corrosion inhibition rate: ≥90% (140∘C)	Self-prepared (containing corrosion inhibitors, stabilizers, and flow-back aids); ready for use after stirring, dissolution, and static degassing.
Simulated Formation Brine	Salinity: 10×104 mg/L; Ionic components: Na^{+},Ca^{2+},Mg^{2+},Cl^{-},SO_4^{2-}	Prepared according to formation water salinity; used for core saturation, permeability measurement, and pipeline cleaning.

2.2 Experimental Apparatus and Equipment

This experiment was conducted using an HTHP (high-temperature and high-pressure) acidizing simulation system and a digital analysis system for acid-etched wormholes. The specific technical parameters are as follows:

96 **Table 2.** Experimental Apparatus and Technical Parameters

Category	Experimental Equipment / Software	Main Technical Specifications / Functional Description
Core Simulation System	HTHP acidizing simulation apparatus (Fig. 1)	Max. temperature: 200 °C; Max. confining pressure: 20 MPa
	Dual-piston constant-flow pump	Range: 0.1~10 mL/min; Accuracy: 0.01 mL/min
	Pressure/differential pressure transducer	Range: 0~1 MPa; Accuracy: 0.001 MPa
	Data acquisition system	Sampling frequency: 1 Hz; Automatic recording of pressure, flow rate, temperature, and mass data
Characterization and Analysis	High-precision full-core CT scanner (Fig. 2)	16-row detector; Tube voltage: 80~160 kV; Tube current: 10~300 mA. Min. scan layer thickness: 0.125 mm; Spatial resolution: 190 μm × 190 μm
	Avizo 2021 software	3D reconstruction, spatial morphology, and quantitative analysis of geometric parameters for acid-etched wormholes
Auxiliary Equipment	Electronic balance	Accuracy: 0.001 g
	Electronic constant-temperature drying oven	Temperature accuracy: ±1 °C
	Pretreatment and accessories	Core cleaning device, ultrasonic cleaner, volumetric flasks, pipettes, and dynamic storage media

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Figure 1. High-temperature and high-pressure (HTHP) acidizing simulation apparatus



Figure 2. CT Scanner and Computer Processing Equipment

2.3 Experimental Design

For the high-temperature (140 °C) carbonate reservoir, a multi-component organic solid acid system with superior retarding performance was selected as the research object. The experiments were conducted in four stages using the single-variable method: optimizing the injection rate first, followed by investigating the effects of acid concentration, temperature, and permeability on acidizing performance. During the experiments, all parameters were kept constant except for the specific factor under investigation. The detailed experimental scheme is as follows:

Injection Rate Optimization: At 140 °C and a 15% acid concentration, an injection rate gradient (0.3~5 mL/min) was set to determine the optimal injection rate for high-permeability cores.

Effect of Acid Concentration: With the temperature fixed at 140 °C and the injection rate at 1 mL/min (the optimal rate), acidizing flow experiments were conducted on high-permeability cores at concentrations of 5%, 15%, and 20% to investigate the impact of concentration on acidizing effectiveness.

Effect of Reservoir Temperature: With the acid concentration fixed at 15% and the injection rate at 1 mL/min, experiments were performed on high-permeability cores at temperatures of 90 °C and 140 °C to explore the influence of reservoir temperature.

Effect of Rock Permeability: At a fixed temperature of 140 °C and 15% concentration, injection rate gradients were established for both high- and low-permeability cores (0.5~4 mL/min for low-permeability; 0.3~5 mL/min for high-permeability). This stage systematically analyzed the influence of permeability on acidizing patterns and evaluated reservoir adaptability.

2.4 Experimental Procedures

2.4.1 Core acidizing flow experiment

Core Pretreatment: The carbonate core samples were dried at 105 °C until a constant weight was achieved. After measuring the baseline physical parameters, the cores were saturated with simulated formation brine for 24 h using the vacuum saturation method to ensure all pores were completely filled.

System Debugging: The acidizing simulation system was preheated for 30 min. The core was then loaded into the core holder, and a confining pressure of 12 MPa was applied via a confining pressure pump. The confining pressure was maintained 2~3 MPa higher than the injection pressure to prevent fluid bypassing (leakage) and core damage.

Thermal Equilibration and Permeability Measurement: The system was heated to the target temperature (90 °C or 140 °C) and maintained for 1 h to reach thermal equilibrium. Simulated brine was then injected at the design flow rate. Once the pressure differential stabilized, the initial liquid-measured permeability was calculated according to Darcy's law.

Acid Injection and Data Acquisition: The injection medium was switched to the multi-component organic solid retarded acid while maintaining a constant flow rate. Data including pressure differential and outlet fluid volume were collected in real-time. The experiment was terminated when the inlet-outlet pressure differential approached zero and a significant volume of acid flowed from the outlet, indicating the successful formation of an acid-etched wormhole (breakthrough).

Post-test Processing and Data Analysis: The pressure was slowly bled off, the core was removed, and the pipelines were thoroughly cleaned. The total volume of acid consumed was recorded, and the Pore Volume to Breakthrough (PVBT) was calculated using the formula PVBT = Vacid / Vpore.

2.4.2 Digital Analysis of Acid-Etched Wormholes

Core Pretreatment: The acid-etched core samples were dried at 105 °C until a constant weight was reached to eliminate interference from residual pore fluids. The core was then placed at the center of the CT scanner's sample stage and aligned with the scanning axis.

CT Scanning Parameter Settings: The dried core was positioned along the central axis of the scanner. The scanning parameters were set as follows: a layer thickness of 0.125 mm, a rotation time of 2 s, a tube voltage of 140 kV, and a field of view (FOV) of 50 mm × 50 mm. A helical scanning mode was adopted, with the tube current maintained at a high rated value to ensure a maximum signal-to-noise ratio (SNR).

Data Acquisition and Storage: A high-precision scan of the entire core was completed. After confirming that the images were clear and free of artifacts, the raw projection data were exported and stored for further analysis.

3D Reconstruction and Quantitative Analysis: The data were imported into Avizo 2021 software for 3D reconstruction following pretreatment steps such as denoising and threshold segmentation. Volume rendering techniques were utilized to generate visual images. Geometric parameters, including wormhole volume, average diameter, length, and the number of branches, were extracted and calculated to achieve a quantitative characterization of the acid-etched morphology.

2.5 Evaluation Indicators for Acidizing Effectiveness

To evaluate the stimulation performance of the multi-component organic solid acid system, a multi-indicator evaluation framework was established, encompassing macroscopic morphology, dynamic processes, and microscopic characterization:

Core Etching Morphology: By observing the degree of dissolution, wormhole distribution, and dimensions on the core end-faces, a macroscopic basis for the acidizing effectiveness is provided.

Pressure Differential Dynamic Curves: The variation of pressure differential over time during acid injection (e.g., peak pressure and pressure drop rate) is analyzed to reflect the real-time development process of the wormholes.

Pore Volume to Breakthrough (PVBT): This indicator quantitatively characterizes the multiples of acid volume required to form a penetrating wormhole. A lower PVBT value indicates higher acid utilization and superior acidizing efficiency.

3D CT Imaging Characteristics of Wormholes: Utilizing 3D reconstructed images and quantitative parameters, the penetration distance, branching degree, and diameter distribution of the wormholes are characterized to reveal their underlying growth mechanisms.

3、Results and Discussion

3.1 Effect of Injection Rate on the Acidizing Performance of Multi-component Organic Solid Acid at 140 °C

Acidizing experiments were conducted at 140 °C with a 15% acid concentration across varying injection rates. Through a multi-dimensional analysis—incorporating etching morphology, pressure differentials, Pore Volumes to Breakthrough (PVBT), and CT imaging—the impact of injection rate on acidizing effectiveness was investigated, leading to the determination of the optimal injection rate.

3.1.1 Core Etching Morphological Characteristics

At 140 °C, the injection rate significantly influences the core etching morphology (Fig. 3). As the flow rate increases (0.3, 0.5, 1, 2, and 5 mL/min), the etching characteristics exhibit a systematic evolution:

Table 3. Summary of the Influence of Injection Rate on Acid-Etched Wormhole Development Characteristics at 140 °C

Injection Rate Type	Specific Rate (mL/min)	Dominant Mechanism	Etching Morphology & CT Characteristics
Low Injection Rate	0.3,0.5	Mass Transfer Controlled (Long residence time)	Severe sheet-like surface dissolution; intense dissolution at the inlet face.
Intermediate Injection Rate	1~2	Kinetic Equilibrium (Balanced mass transfer and reaction)	No significant surface dissolution; pore channels correspond consistently between inlet and outlet.
High Injection Rate	5	Reaction Controlled (High flow velocity)	Large-scale dissolution of matrix pores; generation of dense branching patterns.

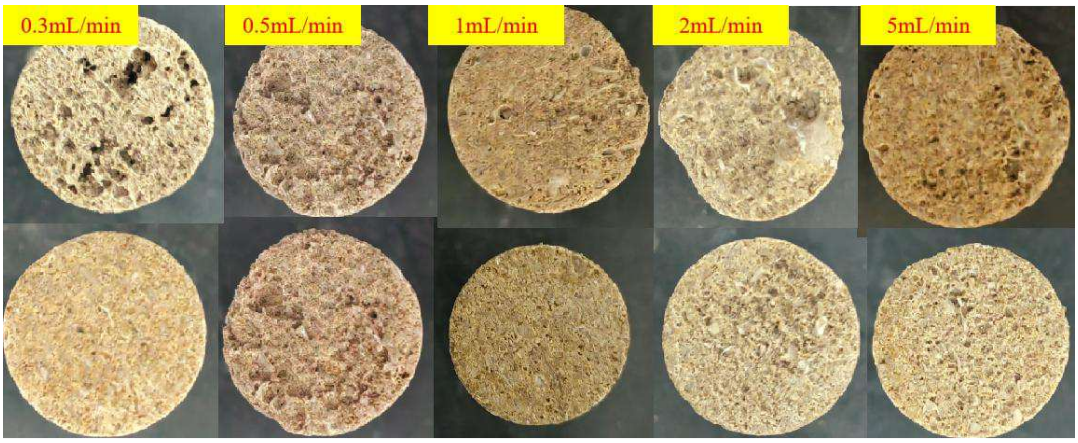

Figure 3. Core end-face etching morphology at different flow rates at 140 °C

The injection rate influences etching by modulating residence time and mass transfer processes. At low rates, prolonged residence time ensures that mass transfer dominates; the extensive diffusion of H^+ leads to severe surface dissolution. Conversely, at high rates, surface reactions dominate, resulting in intense matrix pore dissolution and the formation of numerous shallow, branched wormholes. An

intermediate rate of 1 ~ 2 mL/min achieves a balance between mass transfer and reaction kinetics, promoting the deep migration of acid and the formation of efficient dominant wormholes.

3.1.2 Pressure Differential Curve Characteristics

At 140 °C, the pressure differential curves for injection rates of 0.3, 1, and 5 mL/min (Fig. 4) all follow a characteristic 'gradual rise – rapid decline – approach to zero' trend. The injection rate significantly influences these characteristic parameters:

Table 4. Summary of the Influence of Injection Rate on Acidizing Pressure Differential Response Characteristics at 140 °C

Stage of Pressure Change	Physical Process & Phenomena	Influence of Injection Rate	Quantitative Comparison
I. Pressure Rise Stage	Limited by the flow resistance of the low-permeability core; the pressure differential rises rapidly with injection time.	Positive correlation: Higher rates lead to faster pressure buildup; the time required to reach peak pressure is shorter.	The time to peak at 5 mL/min is only 1/5 of that at 0.3 mL/min.
II. Pressure Decline Stage	Wormhole development enhances permeability, causing the pressure differential to enter a rapid decline phase.	Positive correlation: Higher rates result in higher peak pressures and steeper pressure drop curves.	The maximum pressure drop at 5 mL/min exceeds 0.7 MPa, significantly higher than at low rates.
III. Near-Zero Pressure Stage	Formation of a breakthrough dominant wormhole; pressure is released, and system flow resistance disappears.	Negative correlation: Injection rate is inversely proportional to breakthrough time.	Breakthrough occurs in ~ 10 min at 5 mL/min, while it exceeds 100 min at 0.3 mL/min.

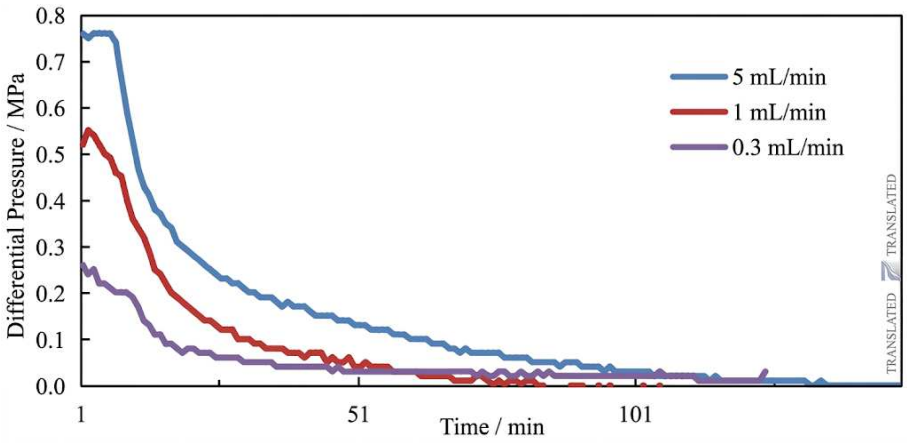

Figure 4. Pressure differential curves at different injection rates

Furthermore, at injection rates of 1 ~ 2 mL/min, the moderate peak pressure and gradual pressure decline indicate stable wormhole development. In this range, the acid–rock reaction and acid transport reach a dynamic equilibrium, identifying it as the optimal injection rate.

3.1.3 Characteristics of Pore Volumes to Breakthrough

At 140 °C, the pore volume to breakthrough (PVBT) at different injection rates exhibits a typical 'U-shaped' curve characteristic as the injection rate increases, initially decreasing and then increasing (Fig. 5).

Table 4. Summary of the effect of injection rate on acid breakthrough volume at 140 °C

Injection Rate Range	Representative Rate (mL/min)	PVBT Characteristics	Primary Causes of Acid Consumption	Efficiency Evaluation
Low Injection Rate	0.3~0.5	High values (>8.0)	Severe face dissolution consumes a large amount of acid, preventing effective transport into the deep formation.	Low efficiency
Moderate Injection Rate	1~2	Minimum values (3.0~4.0)	Face dissolution disappears; acid-rock reaction and transport reach equilibrium, concentrating acid to develop dominant wormholes.	Highest efficiency (Optimal)
High Injection Rate	2~5	Rebound (>5.0)	A large number of branched wormholes are generated, dispersing and wasting a portion of the acid.	Efficiency decline

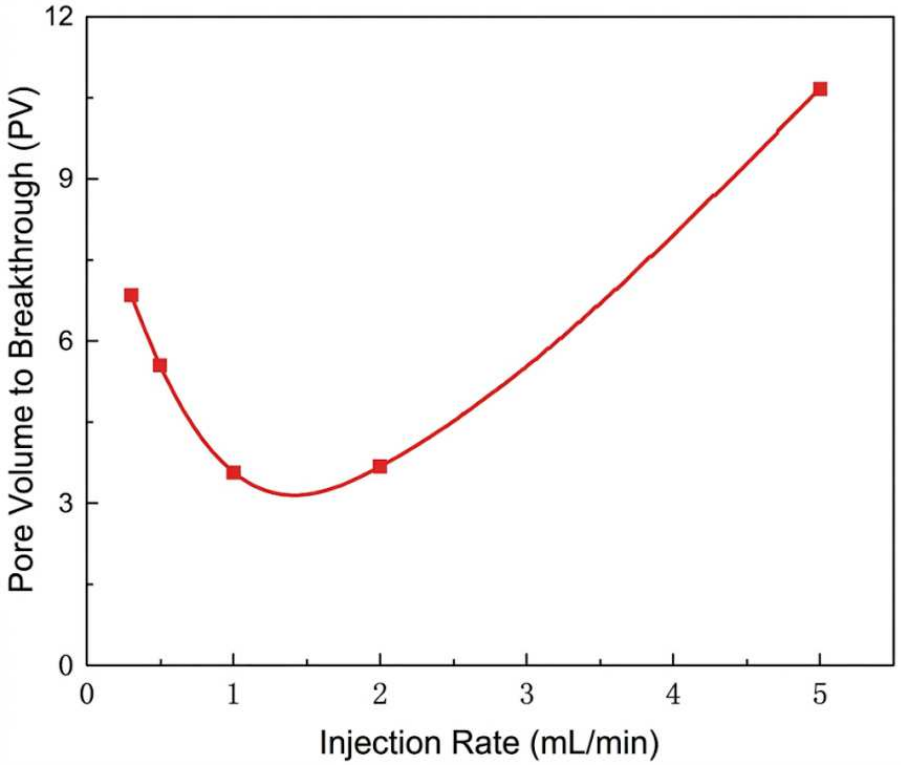

Figure 5. Pore volume to breakthrough at different injection rates and temperatures

In view of the variation patterns of pore volume to breakthrough (PVBT), the acid utilization efficiency reaches its peak at an injection rate of 1~2 mL/min, which is identified as the optimal injection rate for the 15% multicomponent organic solid acid system at 140 °C.

3.1.4 CT 3D Imaging and Quantitative Characteristics of Wormholes

Figure 6 illustrates the 3D CT images of acid-etched wormholes at different injection rates at 140 °C, with flow rates of 0.3, 0.5, 1, 2, and 5 mL/min from left to right. Combined with the quantitative analysis results from Avizo software, significant regularities in the 3D morphology, branching degree, and penetration distance of the wormholes are observed under various injection rates. The specific characteristics are as follows:

Table 6. Summary of Quantitative CT Characterization of Acid-Etched Wormholes at Different Injection Rates at 140 °C

Injection Rate Range	Representative Rate (mL/min)	3D Morphological Characteristics	Average Pore Diameter (mm)	Number of Branches	Penetration Distance (L/L0)	Acidizing Stimulation Evaluation
Low Injection Rate	0.3, 0.5	"Conical" dissolution: Severe dissolution at the inlet, rapidly narrowing with depth.	2.5	<5	<1/2	Low (No continuous channel formed)
Moderate Injection Rate	1~2	"Single" dominant wormhole: Uniform diameter, no significant branching or face dissolution.	0.8~1.0	<3	1.0 (Full breakthrough)	Highest (Effectively connects the reservoir)
High Injection Rate	5	"Multi-branched network": Absence of dominant channel; dense interconnected small pores develop in shallow layers.	0.3	>20	<2/3	Relatively low (Acid consumed by branching)

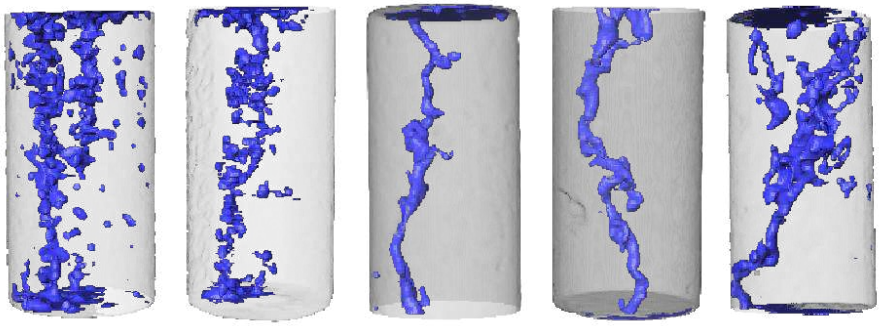

Figure 6. CT Imaging of Wormholes at Different Injection Rates at 140 °C

Based on the integrated analysis of core etching morphology, pressure differential curves, pore volume to breakthrough (PVBT), and 3D CT imaging, the optimal injection rate for the 15% multicomponent organic solid acid system at 140 °C is identified as 1~2 mL/min. At this rate, the acid-etched wormholes exhibit the ideal morphology, with peak acid utilization efficiency and superior stimulation performance.

Compared to conventional acid systems (such as 15% HCl), which typically exhibit higher optimal injection rates (usually > 5 mL/min) at similar temperatures, the optimal rate for the multicomponent organic solid acid in this study is significantly lower. This is attributed to the lower reaction kinetic constant and pronounced retarded nature of the solid acid system. These characteristics allow the acid-rock reaction and transport to reach equilibrium at lower flow velocities, facilitating the formation of dominant wormholes throughout the core while minimizing total acid consumption.

3.2 Effect of acid concentration on the acidizing suitability of multicomponent organic solid acid systems

To determine the optimal concentration for the multicomponent organic solid acid, comparative experiments were conducted using concentrations of 5%, 15%, and 20% at 140 °C and an injection rate

of 1 mL/min (the optimal rate). This study analyzed the influence of acid concentration on the acidizing performance in high-permeability cores.

3.2.1 Core etching morphologies at different acid concentrations

At 140 °C and an injection rate of 1 mL/min (the optimal rate), no significant differences were observed in the core face etching morphologies across the three acid concentrations (5%, 15%, and 20%), as shown in Figure 7. The specific characteristics are as follows:

No significant face dissolution was observed at either the inlet or outlet of the cores for all three concentrations. Both ends developed a moderate number of irregular wormholes with uniform sizes, and their positions generally corresponded between the inlet and outlet. This indicates that at this injection rate, the multicomponent organic solid acid at various concentrations can consistently form effective penetrating wormholes, achieving favorable acidizing performance.

The 5% low-concentration acid produced slightly larger wormhole diameters, while the 20% high-concentration acid resulted in a slightly higher number of wormholes. However, the overall differences were minimal. Based solely on visual observation of the face etching morphologies, it is difficult to effectively distinguish the relative performance of different acid concentrations.

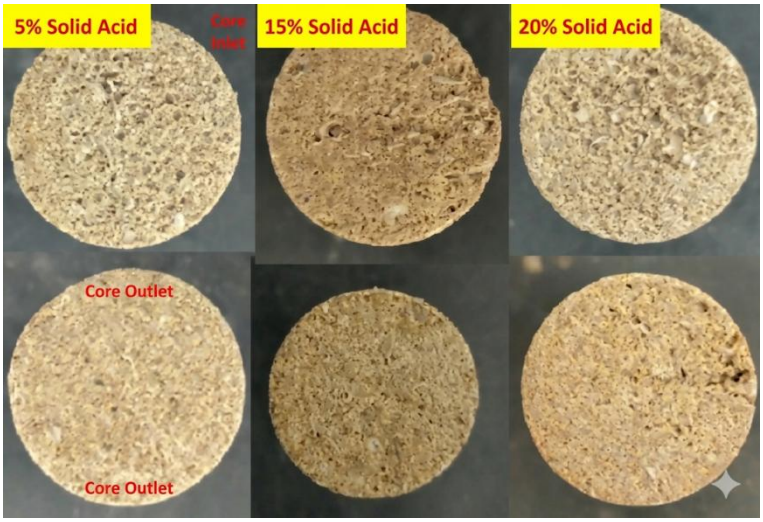

Figure 7. Core face etching morphologies at different acid concentrations at 140 °C

The above results indicate that, at the optimal injection rate, the multicomponent organic solid acid system exhibits a degree of concentration adaptability, achieving favorable etching effects across various concentrations. The pH of the fresh acid for the multicomponent organic solid acid remains around 2 at different concentrations. Since the release of H^+ is primarily controlled by ionization, increasing the acid concentration alone does not significantly elevate the effective H^+ concentration. This phenomenon is a key manifestation of the retarded reaction characteristics inherent in the multicomponent organic solid acid system.

3.2.2 3D CT Imaging Characteristics at Different Acid Concentrations

At 140 °C, the effects of three acid concentrations (5%, 15%, and 20%) on wormhole morphology and branching degree were compared using 3D CT imaging (Figures 8 and 9). The observed regularities are as follows:

Table 7. Effect of acid concentration on wormhole morphology and rate adaptability at 140 °C

Acid Conc. Classification	Specific Conc. (%)	Core Development Morphology	Typical Parameters (at 1 mL/min)	Variable Flow Rate Response	Reaction Mechanism & Adaptability Evaluation

Low Conc.	5	Multi-branched morphology: Unclear main channels with disordered structure.	Numerous branches; average diameter approx. 1.2 mm.	Low rate: Severe face dissolution; High rate: Network-like branching.	Slow H+ release; requires extremely low injection rates to match mass transfer; narrow adaptability.
Medium-High Conc.	15, 20	Single dominant wormhole: Excellent penetration with regular morphology.	Nearly no branching; uniform diameter (0.8 / 0.6 mm).	High rate (5 mL/min): Minor branching, but maintains stable core penetration.	Good match between reaction rate and transport velocity; efficiently builds low-branching dominant channels; strong adaptability.

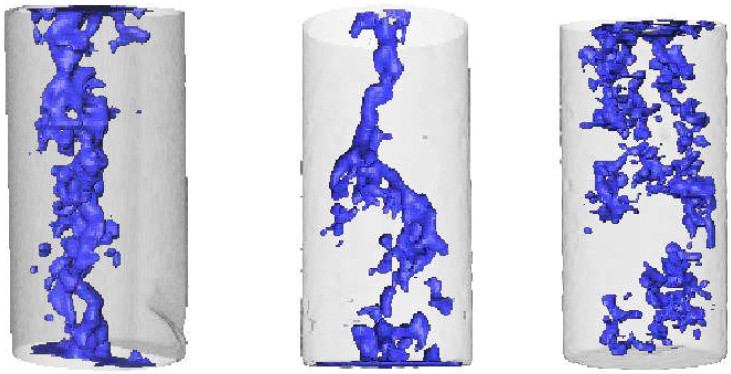

Figure 8. CT imaging of 5% solid acid system

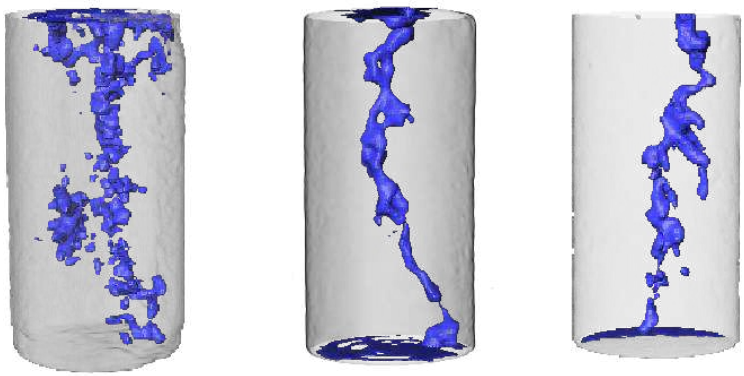

Figure 9. CT imaging of 20% solid acid system

Analysis indicates that, at the optimal injection rate, increasing the acid concentration leads to a gradual reduction in wormhole size, a decrease in the degree of branching, and an extension of the effective penetration distance, thereby significantly enhancing acidizing efficiency.

The core mechanism is as follows: The higher acid concentration moderately increases the H^+ content and accelerates the acid-rock reaction rate. This facilitates more uniform dissolution along the wormhole walls, effectively inhibiting the formation of oversized wormholes and non-productive branches.

3.2.3 Wormhole breakthrough volume characteristics at different acid concentrations

At 140 °C, the influence of acid concentration on the pore volume to breakthrough (PVBT) and the optimal injection rate (Figure 10) is as follows:

Table 8. Summary of the Effects of Acid Concentration on Optimal Injection Rate and PVBT Response Characteristics at 140 °C

Evaluation Dimension	5% Low Concentration Acid	15% – 20% Mid-High Concentration Acid	Evolution Pattern & Physical Mechanism Analysis
Optimal Injection Rate	0.5 mL/min	1.0 ~ 2.0 mL/min	Positively Correlated: Lower concentration leads to slower reaction; low displacement is needed to extend residence time to match the mass transfer process.
Breakthrough Volume (PVBT)	Relatively High: Approx. 5.0	Relatively Low: 2.5 ~ 3.0	Negatively Correlated: Low concentration acid easily forms multi-branched structures, leading to high acid loss in ineffective branches.
Displacement Sensitivity	Extremely High: PVBT curve is steep; highly sensitive to fluctuations in displacement.	Relatively Low: Curve is flat; maintains high efficiency especially for 20% concentration within 1~3 mL/min.	Higher concentration leads to stronger adaptability: High-concentration acid has a higher tolerance for on-site displacement fluctuations.
Construction Stability Evaluation	Relatively Poor: Prone to acidification failure due to improper displacement.	Excellent: Conducive to stable on-site construction and deep penetration.	Mid-high concentration acid can construct main channels more efficiently and reduce construction risks.

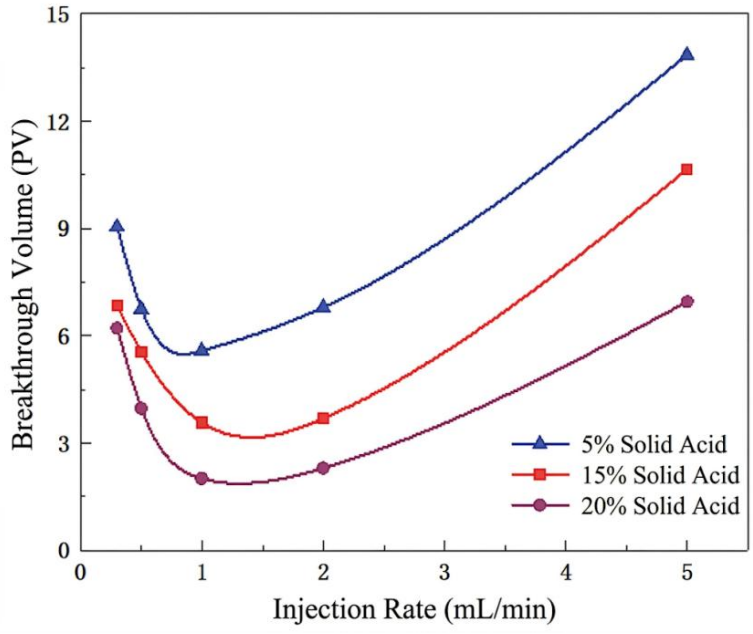

Figure 10. PVBT curves at different acid concentrations.

Comprehensive analysis indicates that the concentration range of 15%~20% is the most suitable for the multicomponent organic solid acid system under high-temperature conditions of 140°C. Within this range, the system exhibits high acidification efficiency, ideal wormhole morphology, and strong adaptability to displacement fluctuations, offering significant advantages for the stimulation of high-

temperature carbonate reservoirs. Specifically, the 15% concentration achieves the optimal balance between acid utilization efficiency and operational adaptability, making it the primary recommended concentration for this system.

It is noteworthy that the total amount of hydrogen ions (H^+) released by the 15% multicomponent organic solid acid upon complete reaction is only equivalent to that of 7%~8% hydrochloric acid (HCl), which is significantly lower than the conventional recommendation of 15%~20% HCl. This is attributed to the fact that multicomponent organic acids undergo stepwise dissociation as temperature rises, resulting in a slower reaction rate that is primarily mass-transfer controlled. Furthermore, the reaction products (acting as a buffer solution) provide a secondary promotional effect on the acid-rock reaction. Consequently, a lower injection rate helps extend the contact time between the acid and the rock, enhancing acid efficiency and promoting the formation of robust dominant wormholes.

3.3 Effect of Reservoir Temperature on the Acidification Performance of Multicomponent Organic Solid Acid Systems

With a fixed acid concentration of 15% and an injection rate of 1 mL/min (the optimal injection rate), experimental temperatures were set at 90 °C and 140 °C to conduct acidification flow tests and digital analysis of acid-etched wormholes on high-permeability cores. The influence of reservoir temperature on acidification performance was analyzed through three dimensions: core etching morphology, CT 3D imaging, and pore volume to breakthrough (PVBT). This approach aims to clarify the regulatory mechanism of temperature on the optimal injection rate.

3.3.1 Core etching morphologies at different temperatures.

Comparing the core end-face etching morphologies at 90 °C and 140 °C (Figures 11 and 2) at an injection rate of 1 mL/min, the influence of temperature on acidification characteristics is as follows:

Table 9. Comparison Summary of Acid-Etched Wormhole Development Characteristics at Different Temperatures (90 °C vs 140 °C)

Evaluation Dimension	90 °C Experimental Characteristics	140 °C Experimental Characteristics	Evolution Pattern & Physical Mechanism
Wormhole Size	Smaller diameter, approximately 0.3 mm.	Significantly increased diameter, approximately 0.8 mm.	Positively Correlated: High temperature accelerates acid-rock reaction kinetics, intensifying the dissolution of wormhole walls.
Distribution & Path	Concentrated in the center; growth path is relatively singular.	More uniform distribution; path tends to be straight and extends toward the side walls.	Directional Development into Deep Zones: High temperature easily induces straight penetration channels, reducing breakthrough resistance and enhancing acidification efficiency.
Surface Dissolution	Slight surface dissolution observed on the core end-face.	Virtually no surface dissolution on the end-face.	Reaction Equilibrium Shift: At high temperatures, acid activity is extremely high, allowing it to rapidly enter deep pores and avoid ineffective residence at the end-face.
Comprehensive Evaluation	Moderate acidification efficiency; acid transport distance is limited.	Superior acidification effect; higher acid utilization rate.	High temperature promotes the formation of effective dominant wormholes by optimizing mass transfer and reaction equilibrium.

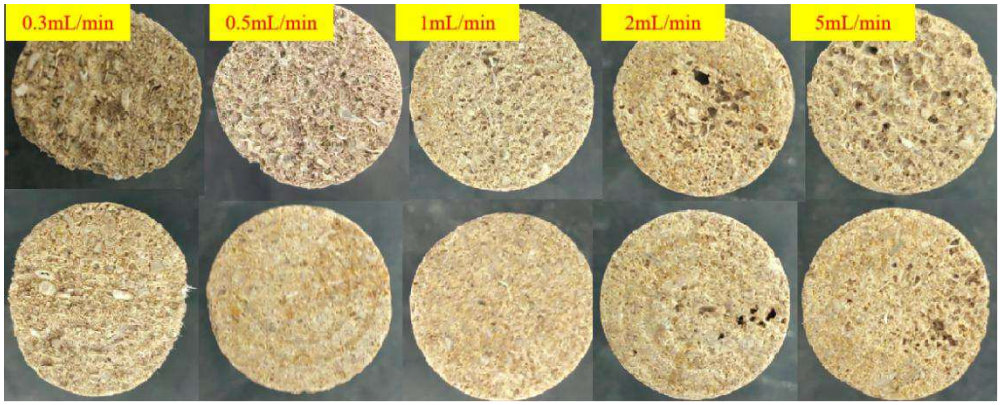

Figure 11. Core end-face etching morphologies at different injection rates at 90 °C.

3.3.2 3D CT imaging characteristics at different temperatures.

Figure 12 illustrates the 3D CT imaging of acid-etched wormholes at different injection rates (0.5, 1, and 5 mL/min) under a temperature of 90 °C. In comparative analysis with the experimental results at 140 °C (Figure 4), it is observed that reservoir temperature exerts a significant regulatory effect on the three-dimensional morphology, branching degree, and longitudinal penetration distance of the wormholes. The specific characteristics are as follows:

1) Low-Temperature Conditions (90 °C): At a low injection rate (0.5 mL/min), a single dominant wormhole tends to form with a long penetration distance. As the rate increases (1~5 mL/min), branching intensifies, leading to a decrease in acidification efficiency. At low temperatures, the acid-rock reaction is limited by the surface reaction rate. Lower injection rates provide sufficient time for dissolution at the wormhole tip, whereas high-speed injection causes rapid acid consumption in shallow layers, resulting in numerous ineffective branches.

2) High-Temperature Conditions (140 °C): A general trend toward surface dissolution is observed at high temperatures. Higher injection rates (1~2 mL/min) are required to form a single dominant wormhole; if the rate is too low (0.3~0.5 mL/min), the results manifest as face dissolution or conical wormholes. At high temperatures, the reaction is extremely rapid, making the mass transfer process the dominant controlling factor. High displacement rates accelerate acid transport and minimize the radial diffusion of H^+ to the rock surface, thereby guiding the acid to extend deeper into the formation.

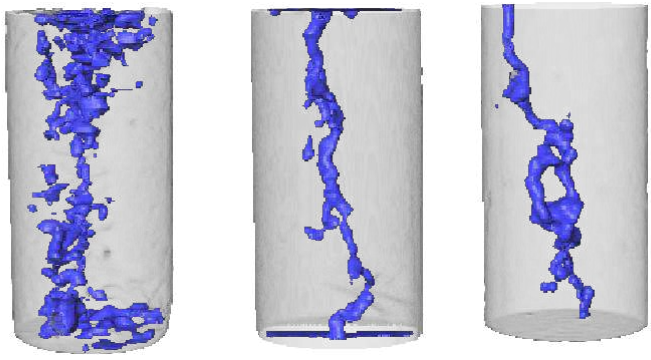

Figure 12. Acidification CT images at 90 °C.

By comparing the CT imaging results at 90 °C and 140 °C, it is clearly observed that the wormhole size decreases as temperature drops. At 90 °C, the average wormhole diameter is approximately 0.4 mm, whereas at 140 °C, it increases to approximately 0.8 mm. This indicates that rising temperatures promote wormhole development, enlarging the diameter and enhancing reservoir permeability.

Notably, as the temperature increases from 90 °C to 140 °C, the acid-etched wormhole diameter increases only gradually. This demonstrates the excellent high-temperature retarding effect of this acid system.

3.3.3 Pore volume to breakthrough (PVBT) characteristics at different temperatures.

Figure 13 illustrates the variation curves of the Pore Volume to Breakthrough (PVBT) as a function of the injection rate at different temperatures. The results indicate that reservoir temperature significantly impacts the dynamic patterns of acidification:

Wormhole breakthrough volume increases with rising temperature: At the same injection rate, the PVBT value at 140 °C is markedly higher than that at 90 °C. The increased temperature enhances the reactivity of the acid-rock interaction, leading to greater ineffective consumption of acid along the wormhole walls and side branches. Consequently, less effective acid reaches the tip, requiring a higher total volume of acid to penetrate the core.

The optimal injection rate shifts toward higher values as temperature increases: At 90 °C, the optimal rate for the multicomponent organic solid acid system is approximately 0.5 mL/min; at 140 °C, this optimal rate shifts to 1~2 mL/min. This aligns with the kinetic characteristics of acid-rock reactions. Higher temperatures increase the reaction rate constant, necessitating a higher injection rate to match the acid transport speed. This effectively controls the reaction site to achieve the best stimulation results. Notably, the reaction rate of this multicomponent organic solid acid at 140 °C is comparable to that of conventional HCl at ambient temperature, demonstrating the system's exceptional retarding properties.

Temperature has a smaller impact on acidification effectiveness than the injection rate: Comparison reveals that changes in the injection rate cause fluctuations in PVBT by orders of magnitude, whereas variations caused by temperature are relatively minor. Among the factors influencing acidification performance, the injection rate is the dominant factor, while temperature serves as a secondary factor.

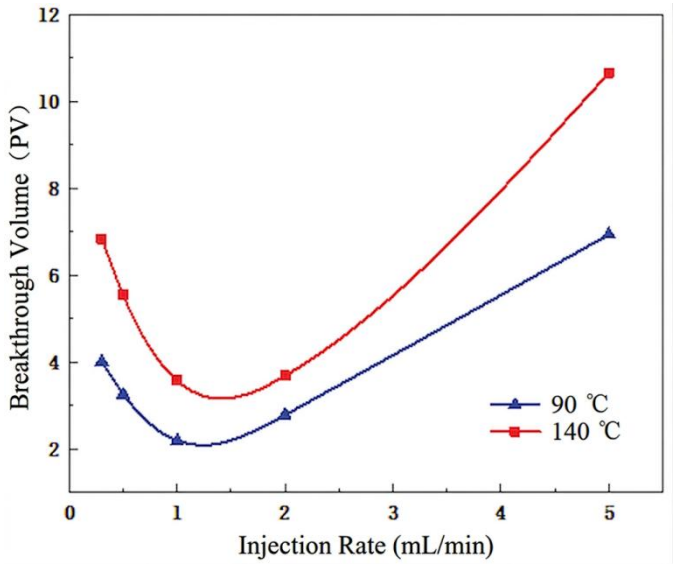

Figure 13. PVBT curves at different temperatures

Comprehensive analysis indicates that reservoir temperature influences acidizing effectiveness by regulating the acid-rock reaction rate. As temperature increases, the reaction rate accelerates, causing the optimum injection rate to shift toward higher values. Although the breakthrough volume (PVBT) increases slightly, the resulting wormholes are more fully developed with larger diameters and longer effective penetration distances, leading to superior overall stimulation results. Therefore, for high-temperature carbonate reservoirs, the injection rate should be appropriately increased to achieve the best performance of the multi-component organic solid acid system.

3.4 Influence of Rock Permeability on the Reservoir Adaptability of Multi-component Organic Solid Acid Systems

With the experimental temperature fixed at 140 °C and the acid concentration at 15%, comparative flow experiments were conducted using high- and low-permeability cores. The reservoir adaptability of the multi-component organic solid acid system was evaluated through three aspects: etching morphology, CT imaging, and breakthrough volume (PVBT).

3.4.1 Core Etching Morphology Under Different Permeabilities

Figure 14 illustrates the end-face etching results of the low-permeability core at 140 °C. Compared with the high-permeability core (Figure 2), the impact of permeability on the etching morphology is significant, with specific differences as follows:

Table 10. Comparison of Acid-Etching Morphologies and Injection Rate Sensitivities for Cores with Different Permeabilities

Evaluation Metrics	Low-Permeability Core (Tight Reservoir)	High-Permeability Core (Conventional Reservoir)	Summary of Patterns and Mechanisms
Surface Dissolution Tendency	Weak: No significant surface dissolution within the range of 0.5~4 mL/min.	Strong: Face dissolution occurs at low rates; large-area surface dissolution at high rates.	Small pore throats in low-permeability cores accelerate acid flow and restrict radial acid diffusion at the end face.
Wormhole Morphological Features	Excellent: Tends to form slender, uniform, and appropriately numbered dominant wormholes.	Variable: Prone to diffuse branching or end-face "vugs/cavities."	Low-permeability cores exhibit stronger guidance for directional dissolution.
Injection Rate Sensitivity	Low: Maintains good morphology across a wide discharge range (up to 4 mL/min).	Extremely High: Effective wormholes form only within a mid-speed range of 1~2 mL/min.	High-permeability cores are more sensitive to fluctuations in discharge rates.
Fracturing/Branching Performance	Stable morphology; branching development is limited even at high discharge rates.	Fluctuates with rate; highly susceptible to inefficient diffuse branching.	Low-permeability structures force acid to concentrate and migrate through a few dominant pore paths.
Comprehensive Evaluation	Superior Adaptability: High efficiency in acid utilization.	Fair Adaptability: Requires strict control of operational parameters.	Multi-component organic solid acids are better suited for tight, low-permeability reservoirs.

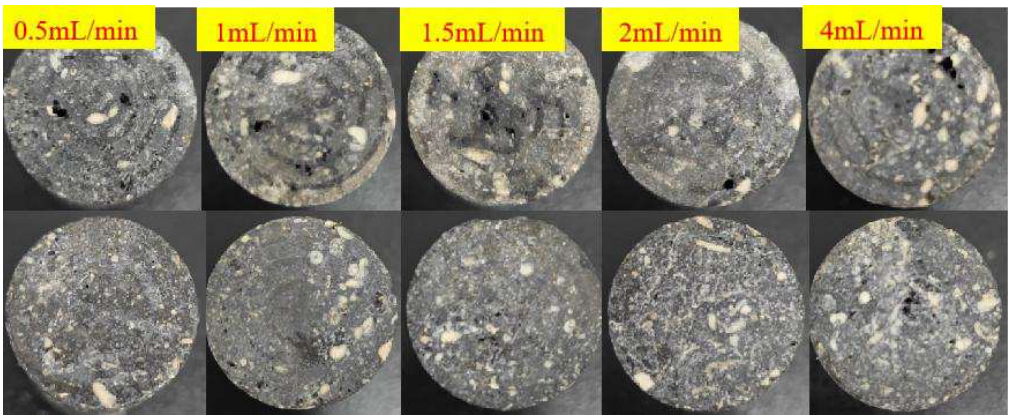

Figure 14. Etching morphology of low-permeability cores at 140 °C (high and low permeability must be labeled)

The primary reason for these differences is that low-permeability cores possess narrow pore throats and low porosity. At the same injection rate, the acid flow velocity within these pores is higher, which restricts the mass transfer process and hinders the diffusion of H^+ to the core surface, resulting in a lower degree of surface dissolution. In contrast, high-permeability cores feature larger pore throats where the acid flows more slowly and has a longer residence time; this allows H^+ to diffuse more easily to the core surface, leading to severe surface dissolution.

3.4.2 3D CT imaging characteristics under different permeabilities

Figure 15 displays the 3D CT imaging results for the low-permeability core at 140 °C. Compared to the high-permeability core (Fig. 4), it is evident that permeability exerts a significant regulatory effect on the spatial development and branching evolution of wormholes:

Table 11. Spatial Evolution and Microscopic Mechanisms of Acidized Wormholes: A Comparative Study of High vs. Low-Permeability Cores

Evaluation Dimension	Low-Permeability Core Characteristics (Tight Reservoir)	High-Permeability Core Characteristics (Conventional Reservoir)	Evolution Law and Micro-Mechanism Analysis
Wormhole Structural Features	Single Main Wormhole: Few branches; slender morphology with smooth walls.	Multi-branched Morphology: No obvious main channel; presence of lateral branches; structure tends to be complex.	Differential Directional Dissolution: Low-perm structures force acid to concentrate in dominant pores, inhibiting radial diffusion.
Pore Diameter and Penetration	Uniform Diameter Distribution: Strong longitudinal penetration; stable penetration through the full length of the core.	Uneven Diameter Distribution: Characterized by "front-end development, back-end branching" in deep sections.	Energy Concentration Effect: Acid activity in low-perm cores concentrates at the tip, driving directional growth of the main channel.
Acid Transport Path	Efficient Deep Transport: Reaction is highly concentrated in a few dominant pore paths.	Dispersive Diffusion: Acid easily leaks laterally toward surrounding large pore throats.	Pore-Throat Constraint Mechanism: Narrow pore throats limit ineffective acid expansion, reducing energy loss from lateral branch construction.

Comprehensive Evaluation	Excellent Acidizing Effect: Easily forms a single main hole that efficiently connects the reservoir.	Limited Deep Development: Main channel development is restricted; acid utilization rate is average.	Multi-component Organic Solid Acid has stronger fracture-inducing guidance capabilities in low-permeability cores.

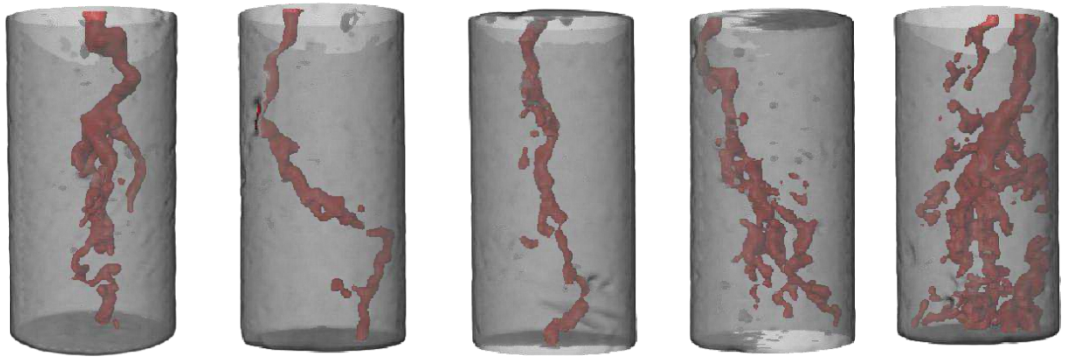

Figure 15. CT images of low-permeability cores under 140 °C

3.4.3 Wormhole Breakthrough Volume (PVBT) vs. Core Permeability

Figure 16 displays the relationship between pore volumes to breakthrough (PVBT) and injection rate for various permeability cores at 140 °C. The data highlights how permeability dictates the dynamic behavior of the acidizing process:

Table 12. Comparison of Acid-Etched Morphology and Injection Rate Sensitivity Across Different Permeabilities

Evaluation Dimension	Low-Permeability Core Characteristics	High-Permeability Core Characteristics	Summary of Trends and Mechanism Analysis
Curve Morphology	U-shaped Curve: As the rate increases, the trend follows a "decrease-then-increase" pattern.	U-shaped Curve: As the rate increases, the trend follows a "decrease-then-increase" pattern.	Commonality: Injection rate is the dominant factor controlling the balance between acid-rock reaction and mass transfer.
Optimum Injection Rate	1.0 ~ 1.5 mL/min	1.0 ~ 2.0 mL/min	Rate Shift: Low-permeability reservoirs can reach the ideal acidizing state at relatively lower flow rates.
Breakthrough Volume (PVbt)	Relatively Low: 1.5 ~ 2.0	Relatively High: 3.0 ~ 4.0	Efficiency Difference: The amount of acid required for penetration in low-perm cores is reduced by approximately 50%.
Acid Utilization Efficiency	Extremely High Efficiency: Reactions are more targeted and focused.	Good Efficiency: Highly susceptible to fluctuations in injection rate.	Multi-component organic solid acid exhibits superior compatibility within tight, low-permeability reservoirs.

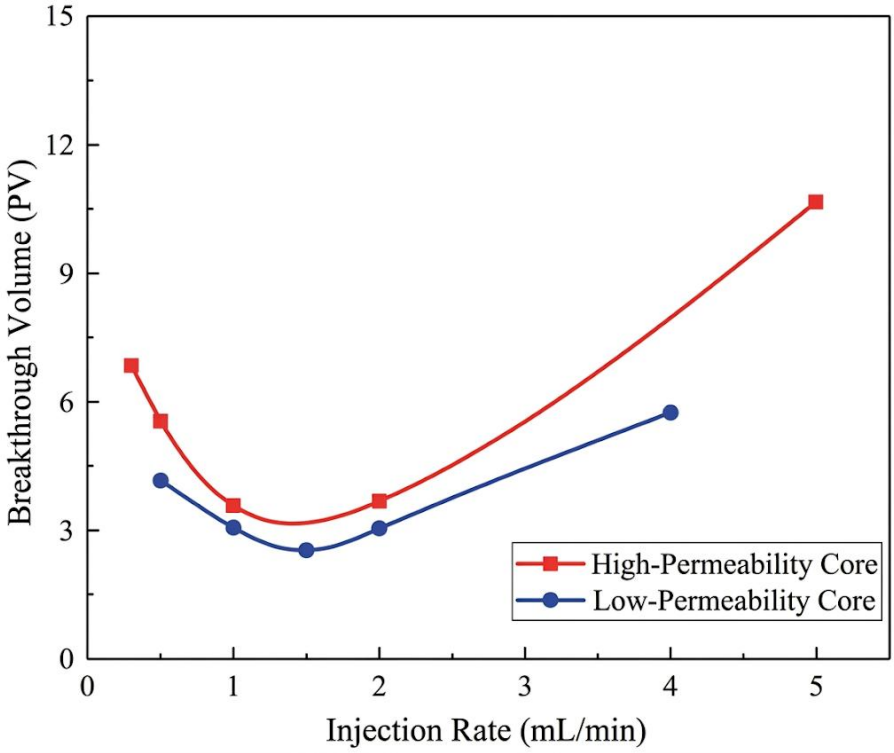

Figure 16. PVBT vs. Injection Rate for Different Permeabilities

Comprehensive analysis of etching morphology, CT imaging, and PVBT indicates that the multi-component organic solid acid system exhibits superior acidification compatibility for tight, low-permeability carbonate reservoirs. The underlying mechanisms are as follows:

A. Low-Permeability Reservoirs: Significant Development of Dominant Flow Channels

The narrow pore-throat structures effectively restrict the radial diffusion and random channeling of the acid, fundamentally preventing surface dissolution and the formation of multi-branched wormholes. The acid is highly concentrated within a few dominant pores, resulting in higher flow velocities that promote the development of a single, penetrative main wormhole. This leads to high acid utilization efficiency and excellent acidification performance.

B. High-Permeability Reservoirs: Enhanced Tendency for Dispersive Dissolution

Coarse pore-throat structures cause the acid to diffuse and channel easily, increasing the tendency for surface dissolution and lateral branching. This results in rapid acid consumption, which relatively diminishes the targeting efficiency and the effective stimulation distance of the acidification process.

4 Discussion

4.1 Wormhole Propagation Mechanisms at Elevated Temperatures

In high-temperature carbonate reservoirs, the interaction between multi-component organic solid acids and the rock matrix is a dynamic process coupling acid transport, mass transfer diffusion, and acid-rock reaction. The morphology of the resulting wormhole is determined by the relative relationship between the mass transfer rate and the reaction rate. An optimal, single penetrative main wormhole is formed only when these two reach a dynamic equilibrium.

1) At Low Injection Rates:

The acid residence time is long, allowing H^+ to fully diffuse to the face and pore walls, which causes the mass transfer rate to significantly exceed the reaction rate. This results in severe surface dissolution

and thick, conical wormholes, preventing the acid from effectively transporting into the deeper parts of the formation.

2) At High Injection Rates:

The acid flow velocity is too high, and while the acid-rock reaction occurs rapidly in the shallow layers, the overall consumption is dominated by these near-wellbore regions. This leads to a reaction rate that outpaces effective mass transfer into a single channel. Consequently, acid is heavily consumed by shallow branching structures, the main wormhole remains indistinct, and deep penetration is difficult to achieve.

3) At the Optimum Injection Rate (1.0~2.0 mL/min):

Within this range, the mass transfer and reaction rates are perfectly matched. H^+ ions are concentrated on the wormhole wall reactions, and the speeds of acid transport and dissolution are synchronized. This forms a single, penetrative main wormhole without surface dissolution, achieving maximum acid utilization.

Factors such as acid concentration, reservoir temperature, and rock permeability regulate wormhole morphology by shifting the equilibrium point of these rates. An increase in concentration or temperature accelerates the acid-rock reaction; to restore the mass transfer-reaction balance, the injection rate must be increased accordingly to speed up acid transport. Conversely, a decrease in permeability accelerates flow within dominant pores while slowing the radial mass transfer and diffusion of the acid. In this case, the injection rate should be appropriately reduced to ensure that the mass transfer and reaction rates reach a new equilibrium at a lower flow velocity.

4.2 Synergistic Optimization Principles for Acidizing Parameters of Multi-component Organic Solid Acid Systems

Based on multi-factor experimental results, the parameter optimization of the multi-component organic solid acid system should adhere to the core principles of "Rate Matching, Concentration Adaptation, and Temperature Regulation":

Table 13. Synergistic Optimization Principles for Acidizing Parameters of Multi-component Organic Solid Acid Systems

Optimization Principle	Core Control Logic	Typical Application Parameters (140 °C, 15% Concentration)	Quantitative Evolution Laws & Engineering Recommendations
Rate Matching	Core Principle: Balance acid transport velocity with acid-rock reaction rate to achieve mass transfer-reaction equilibrium.	Optimum Injection Rate: 1.0 ~ 1.5 mL/min (for low-permeability reservoirs).	Injection rates must be adjusted in real-time based on reservoir physical properties and acid characteristics to inhibit ineffective branching.
Concentration Adaptation	Chemical Kinetics Control: Acid concentration should positively correlate with reservoir temperature to balance dissolution capacity.	Medium-to-High Concentration: 15% ~ 20% (for high-temperature reservoirs ≥ 140 °C).	High Temp: Use medium-high concentrations to control wormhole branching; Low Temp: Appropriately reduce concentration to avoid surface dissolution.
Temperature Regulation	External Boundary Response: Temperature determines the reaction rate constant; injection rates must be adjusted to counteract temperature-induced negative effects.	Synergistic Increment: As temperature rises, the injection rate must be increased synchronously.	Quantitative Law: For every 50 °C increase in temperature, the optimum injection rate needs to increase by approximately 0.5 ~ 1.0 mL/min.

4.3 Reservoir Adaptability and Field Application Recommendations for Multi-component Organic Solid Acid Systems

The multi-component organic solid acid system demonstrates excellent adaptability in high-temperature (140 °C), tight, low-permeability carbonate reservoirs. Based on the laboratory experimental results, the following engineering recommendations are proposed:

Table 14. Field Application Recommendations and Research Outlook for Multi-component Organic Solid Acid Systems

Category	Key Stages	Core Indicators & Technical Recommendations	Engineering Significance & Control Logic
Reservoir Selection	Target Layer Criteria	Permeability: 1~5 mD; Temperature: 120–180 °C.	Fully leverage the retardation advantages of multi-component organic acids to maximize acidification stimulation potential.
Process Parameter Design	Acid System & Flow Rate	At 140 °C: Recommended 15% concentration; injection rate 1.0~1.5 mL/min.	Ensure matching between acid transport velocity and acid-rock reaction rate at high temperatures.
	Pressure Control	Recommended confining pressure: 1.2~1.5 times the reservoir pressure.	Guide effective acid transport into the deep formation and inhibit ineffective radial diffusion.
Construction Process Control	Sudden Pressure Rise Response	Appropriately reduce the flow rate.	Address obstructed wormhole development by extending reaction time to induce main channel growth.
	Sudden Pressure Drop Response	Appropriately increase the flow rate.	Inhibit face dissolution or excessive branching to correct the acidification path.
Future Research Directions	Multi-scale Simulation	Conduct large-scale physical simulations and field trials.	Comprehensively consider the complex effects of heterogeneity, natural fractures, and geomechanical coupling.
	Comparative Evaluation	Comparative experiments between conventional and novel acid systems.	Quantify the cost-reduction and efficiency-enhancement benefits in high-temperature

5 Conclusions

This study focuses on high-temperature (140°C) tight, low-permeability carbonate reservoirs. Utilizing a high-temperature/high-pressure (HTHP) acidification simulation system and high-resolution core CT scanning, we conducted experimental research on the parameter optimization and reservoir adaptability of a strongly retarded multi-component organic solid acid system. The effects of injection rate, acid concentration, reservoir temperature, and rock permeability on acidification performance were systematically investigated. This work reveals the development mechanism of acid-etched wormholes under high-temperature conditions and clarifies the optimal acidizing parameters and reservoir adaptability of the retarded system. The primary conclusions are as follows:

Clarification of Optimal Process Parameters: At 140°C and a 15% acid concentration, the optimal injection rate is 1.0~2.0 mL/min. At this rate, mass transfer and reaction rates reach a dynamic equilibrium, forming a single penetrative main wormhole. This yields the minimum breakthrough volume (PVBT of 3~4) and the highest acid utilization efficiency.

Synergistic Effects of Concentration and Rate: Acid concentration significantly influences acidification morphology. At 140°C, the suitable concentration range is 15%~20%. Specifically, the 15% concentration demonstrates the best adaptability to injection rate fluctuations while maintaining high acid utilization.

Temperature Regulation of Development Modes: As temperature increases, acid-rock reactivity enhances, shifting the optimal rate toward higher values (from 0.5 mL/min at 90°C to 1.0~2.0 mL/min at 140°C). In high-temperature environments, wormholes develop more fully with larger diameters. The impact of injection rate on acidification performance is significantly stronger than that of temperature, highlighting the system's superior high-temperature retardation performance.

Excellent Reservoir Adaptability: Permeability is the critical factor determining adaptability. Compared to high-permeability cores, low-permeability cores (1~5 mD) more easily form main wormholes with low branching, resulting in an approximately 40% reduction in PVBT. The results confirm the excellent compatibility of this acid system with high-temperature tight reservoirs.

Theoretical Mechanisms and Optimization Principles: It is established that wormhole morphology is governed by the "mass transfer-reaction" balance. We propose the synergistic optimization principles of "Rate Matching, Concentration Adaptation, and Temperature Regulation," providing a theoretical basis for the dynamic adjustment of field pumping rates and concentrations.

The results of this study provide critical theoretical foundations and technical support for parameter optimization and field implementation of multi-component organic solid acid systems in high-temperature carbonate reservoirs. This work holds significant theoretical importance and engineering value for enhancing acidification stimulation, extending effective treatment life, and achieving production increases in high-temperature oil and gas reservoirs.

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