University of Miskolc
Faculty of Earth Science and Engineering
Petroleum and Natural Gas Institute

MŰSZAKI FÖLDTUDOMÁNYI KAR

Thesis of the doctoral dissertation (PhD)

MATRIX ACIDIZING IN CARBONATE RESERVOIRS:

OPTIMIZATION OF CARBONIC ACID INJECTION AND INNOVATIVE ACID DIVERSION TECHNIQUES

Author:

Abdulameer Almalichy

Scientific Adviser:
Assoc. Prof. Zoltan Turzo

Mikoviny Sámuel Doctoral School of Earth SciencesHead of the Doctoral School: **Prof. Dr. Péter Szűcs**

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Chapter I: Summary

Matrix acidizing is a stimulation technique used to remove the damaged zone around the wellbore caused by drilling and completion. In this process, the intended acid is pumped into the wellbore at a pressure below the formation breakdown pressure, thereby avoiding formation fractures. When injected, acid penetrates carbonate formations, dissolving carbonate minerals and generating conductive flow channels called wormholes that enhance well productivity. Hydrochloric acid (HCl) is preferred due to its cost-effectiveness and strong ability to dissolve carbonate rocks, making it an ideal choice for matrix acidizing. Its reaction products are typically soluble, preventing clogging, and its low cost makes it an economical choice for enhancing oil production. However, HCl also has notable drawbacks, including its rapid reaction with carbonates at high temperatures, which causes face dissolution and high acid volume consumption, thus limiting deep penetration into the formation. Additionally, it causes severe tubing corrosion, resulting in high inhibition costs.

To overcome these drawbacks, carbonic acid, which consists of water and carbon dioxide (CO_2), can be considered an environmentally friendly alternative to hydrochloric acid. The gradual increase in CO_2 emissions is causing severe environmental and economic concerns regarding global climate change, and utilizing large volumes of CO_2 in industrial projects can reduce greenhouse gas emissions. Over the past decade, significant attention has been directed toward CO_2 injection for enhanced oil recovery (EOR) and carbon capture and storage (CCS) as promising approaches to achieving zero-net carbon. Using carbonic acid as a stimulation acid in carbonate reservoirs can reduce emissions and mitigate the corrosion issues common with HCl acidizing, while also improving permeability, removing drilling-induced formation damage, and increasing production.

Creating a long, dominant wormhole is a primary objective during matrix acidizing, and finding the optimal injection rate is crucial for achieving the longest penetration radius with the minimum acid volume. Experimentally, the optimum injection rate is determined by the minimum injected acid pore volume required to generate a wormhole in a core sample, a parameter known as the minimum pore volume to breakthrough (PVBT). This parameter is influenced by factors such as rock mineralogy, acid type, formation temperature, permeability, and core dimensions.

In the first part of the research, since each acid has an optimum injection rate, similar core-flooding experiments were conducted with carbonic acid to determine its optimum injection conditions.

A major limitation of traditional acidizing techniques is their tendency to flow into high-permeability zones, leaving low-permeability regions untreated. This selective flow reduces the overall effectiveness of the acidizing treatment, resulting in poor reservoir stimulation. Diversion techniques have been developed to overcome this limitation and are generally categorized into mechanical and chemical methods. Mechanical diversion relies on physical barriers to block high-permeability areas, while chemical diversion uses specialized fluids to alter the acid's flow paths. Foam-based acids can effectively block high-permeability zones and slow the acid–rock reaction, but they often suffer from poor stability, especially in high-temperature reservoirs. Emulsified acids can penetrate deeper and offer corrosion protection, but they require complex preparation, have high pumping friction, and are unsuitable for low-temperature wells or fine-particle production. Polymer-based in-situ gelled acids provide strong diversion but can leave damaging residues, suffer from crosslinker precipitation at high temperatures, and lose efficiency in high-permeability contrast cases. In contrast, viscoelastic surfactant (VES)-based self-diverting acids offer high thermal stability, residue-free cleanup, effective diversion in high-salinity environments, and easy viscosity breakdown after treatment, thereby minimizing formation damage while ensuring selective stimulation.

The second part of this research introduces a novel approach that integrates carbonic acid with a viscoelastic surfactant (VES) to divert acid in a heterogeneous carbonate reservoir. This combination aims to enhance acid distribution and deliver both environmental and operational benefits, including reduced hydrochloric acid consumption, minimized corrosion, and alignment with CCS objectives.

In the final part of this study, and unlike previous laboratory experiments that relied on conventional single-core or dual-core flooding systems, a new method is proposed for simulating matrix acidizing in horizontal wells by incorporating five separate injection points and two outlet lines. This design provides a more representative simulation of flow behavior in horizontal wells and allows for direct observation of wormhole initiation, competition, and propagation in heterogeneous reservoirs.

The objectives of this dissertation are:

1. Introducing carbonic acid as a matrix acid for carbonate formations and studying its effects on wormhole generation, permeability enhancement, and porosity improvement while determining its optimum injection rate.

2. Developing a novel approach by effectively mixing carbonic acid with viscoelastic surfactants (VES) to acidize heterogeneous carbonate formations.
3. Introduce a novel design for studying acid diversion, providing an alternative to the conventional designs commonly used in the literature.

Chapter II: Conducted Analyses, Experimental Work, and Methodology

This research was conducted in three interlinked phases, supported by an extensive laboratory setup with high-pressure/high-temperature (HP/HT) equipment.

2.1. Optimization of Injection Rates Using Carbonic Acid

This phase was designed to determine the optimal injection rate for carbonic acid during carbonate rock stimulation. The experiment involved flooding four Indiana limestone core samples at different, constant injection rates (0.5, 1, 2, and 5 cm^3/min). The objective was to see which rate could create a "wormhole" (a dominant flow channel) through the core using the least amount of acid, a key factor for efficiency in field applications.

2.1.1. Methodology of Collecting Materials

- **Core Samples:** Four Indiana limestone core samples (2.5" length, 1.5" diameter) with initial porosities of 12.99-15.41% and permeabilities of 8-12 mD were used. XRD measurements confirmed 100% calcite composition.
- **Fluids:** Carbonic acid was prepared by mixing 30% CO_2 and 70% fresh water using a high-pressure/high-temperature accumulator. The process involved precise filling, controlled transfer of fresh water to the CO_2 accumulator, manual mixing for 10 minutes, and equilibration at 60°C (Figure 1).

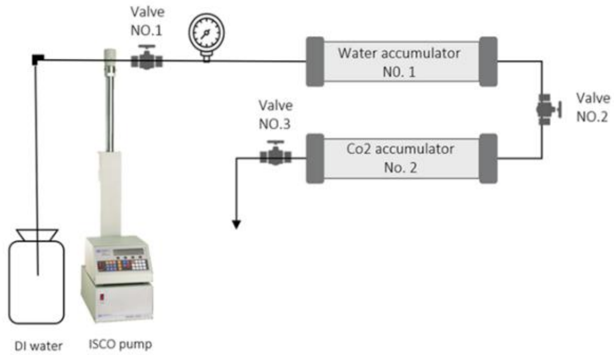


Figure 1 Schematic diagram of the carbonic acid preparation system

2.1.2. Conducted Analyses

- **Petrophysical Analysis:** Before and after each flood, the core's porosity was measured with a helium porosimeter, and its permeability was estimated.
- **Pressure Profile Analysis:** During the flooding experiment conducted by the flooding system in Figure 2, pressure sensors continuously recorded the pressure drop across the core. The moment this pressure dropped to zero indicated the "breakthrough" of the wormhole.
- **Wormhole Morphology Analysis:** After the experiment, each core was dried and scanned using a micro-CT scanner. This provided a 3D visualization of the wormhole, enabling analysis of its shape (e.g., dominant, branched, conical) and calculation of its volume.
- **ICP Analysis:** Effluent fluid collected from the core's outlet was analyzed using an Inductively Coupled Plasma (ICP) spectrometer to measure dissolved calcium ion concentration, which directly reflects how effectively the acid dissolved the limestone.

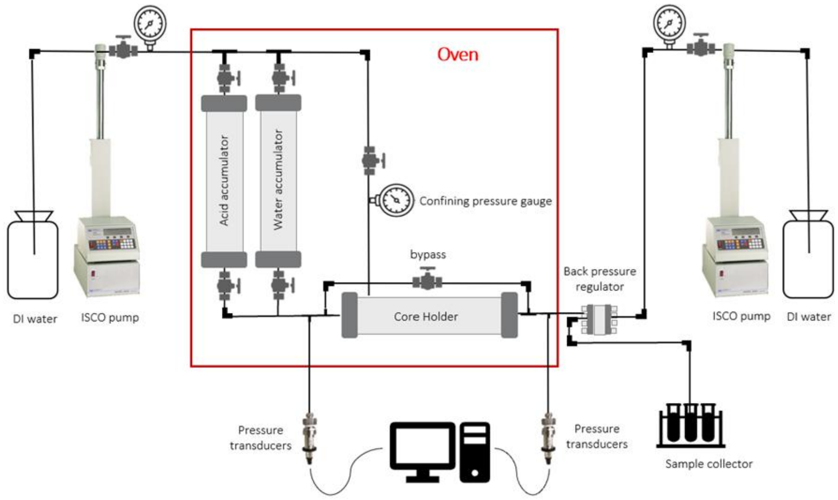


Figure 2 Schematic diagram of a single-core flooding system

2.1.3. Resources Exploited and Applied

- **Core Flooding System:** A high-pressure/high-temperature (HP/HT) flooding apparatus was the central resource.
- **Pumps and Regulators:** A Teledyne ISCO syringe pump ensured precise, constant injection rates, while a back-pressure regulator simulated reservoir pressure.
- **Analytical Instruments:** A Helium Porosimeter (AP-608), a micro-CT scanner, and a Shimadzu ICP Spectrometer were the key analytical tools.

2.2. Acid Diversion Using a Dual-Core Flooding System

This phase introduces a novel approach to integrating carbonic acid with viscoelastic surfactant (VES) for acid diversion in heterogeneous carbonate reservoirs. This approach aims to enhance acid distribution and offers environmental and operational benefits.

2.2.1. Introduction

This set of experiments tested a novel method for treating heterogeneous formations, where acid tends to flow only into the high-permeability zones. The experiment involved flooding two core samples at the same time (Figure 3), one with high permeability and one with low permeability, to see whether a Viscoelastic Surfactant (VES) mixed with carbonic acid could effectively "divert" the flow and treat both cores. This was compared to the performance of hydrochloric acid (HCl) with and without VES.

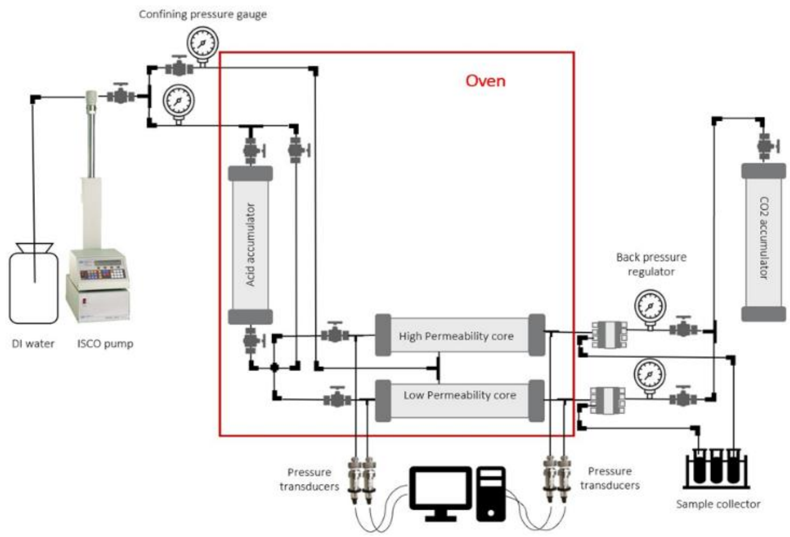


Figure 3: Dual-core flooding system

2.2.2. Methodology of Collecting Materials

- **Core Samples:** Indiana limestone cores were selected and clustered by permeability to create pairs of high-permeability (26-33 mD) and low-permeability (4 mD) samples.
- **Fluids:** Several acid systems were prepared. The key system involved mixing carbonic acid with 10 wt% $CaCl_2$ and 6 wt% of a newly developed VES (FTS-20). For comparison, systems of 15 wt% HCl were also prepared, both with and without the VES additive.

2.2.3. Conducted Analyses

- **Rheological Analysis:** The viscosity of the VES fluids was measured at 60°C using a Chandler HPHT Viscometer. This was critical to confirm that the liquid would thicken under the right conditions to block high-permeability zones.
- **Pressure and Breakthrough Analysis:** Pressure drops across both cores were monitored simultaneously. The breakthrough times for each core were compared to determine whether diversion was successful (i.e., whether the low-permeability core was treated in a similar timeframe to the high-permeability one).
- **CT Scan Visualization:** After the flooding, both cores were scanned with a CT scanner to visually confirm the presence and shape of wormholes, providing definitive proof of acid diversion.

2.2.4. Resources Exploited and Applied

- **Dual-Core Flooding System:** A specialized setup featuring two parallel HP/HT Hastelloy core holders placed inside an oven.

- **Fluid Preparation:** A Silverson L5M overhead stirrer was used to homogenize the complex VES and acid mixtures.
- **Analytical Instruments:** A Chandler HTTP 5550 Viscometer for rheology and a CT scanner for post-flood imaging.

2.3. Acid Diversion Using a Novel Single-Core Design

This phase evaluates a newly developed single-core holder for advanced acid placement.

2.3.1. Introduction

This research phase developed a new experimental method to simulate the injection of acid into long, horizontal wells. A novel core holder was designed with five injection points along its length and two outlets at the ends (Figure 4 and Figure 5). Experiments were conducted to determine how acid would be distributed from multiple injection points and whether a VES could prevent a single injection point from dominating the flow, thereby ensuring the entire length of the wellbore is stimulated.

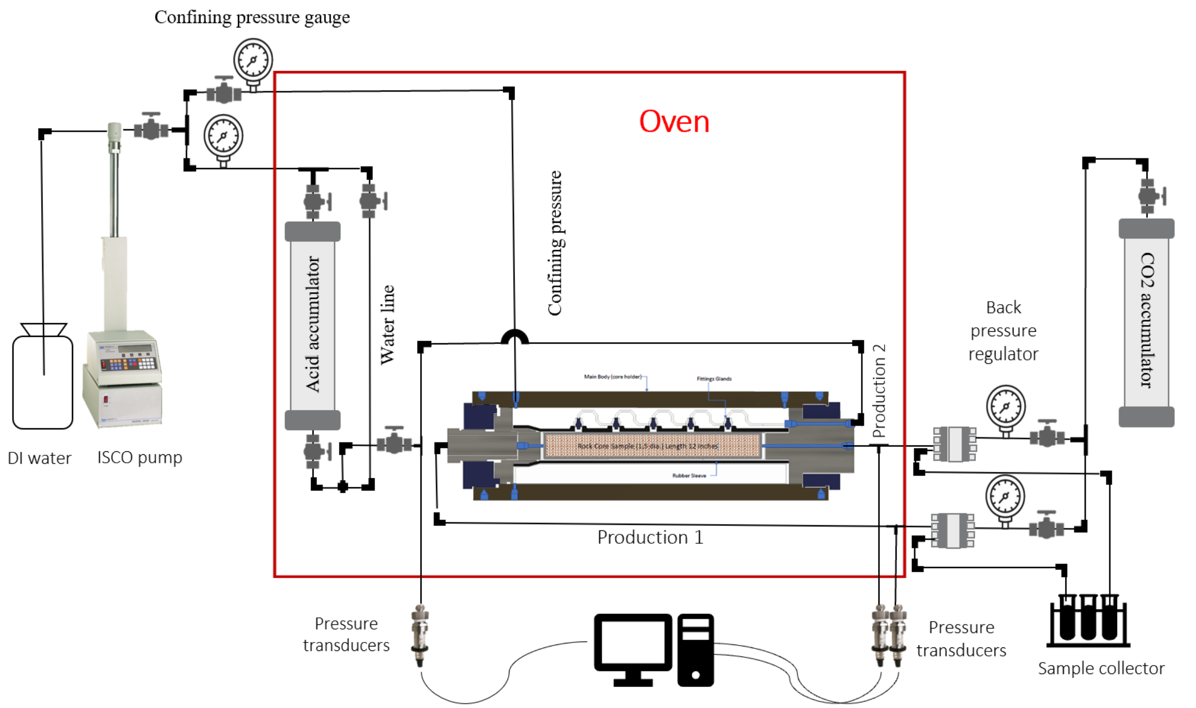


Figure 4 Schematic drawings of the laboratory flooding system

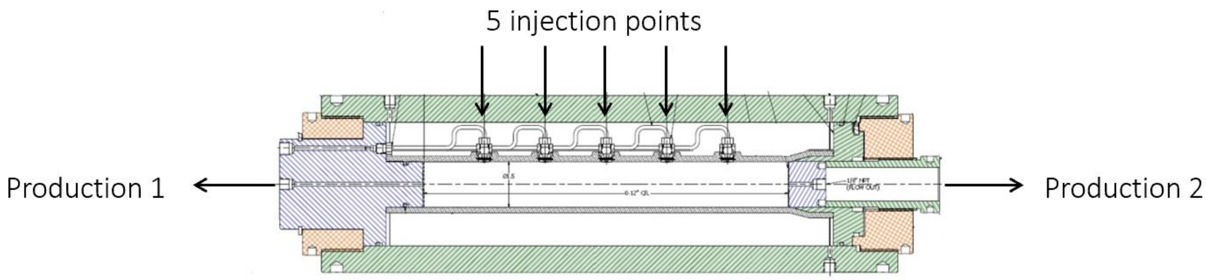


Figure 5: Illustration of injection points and production points

2.3.2. Methodology of Collecting Materials

- Core Samples: Long Indiana limestone cores (6 and 12 inches) were used. For one experiment, two 6-inch cores with different permeabilities (10 mD and 50 mD) were used simultaneously in the setup to simulate a heterogeneous horizontal well.
- Chemicals: The acid systems were prepared using 15 wt% HCl, 1 wt% corrosion inhibitor, 10 wt% $CaCl_2$, and 6 wt% VES. The chemicals were mixed using a corrosion-resistant titanium overhead stirrer.

2.3.3. Conducted Analyses

- **Multi-Point Pressure Analysis:** Pressure was monitored at both outlets. The breakthrough times at each outlet revealed which injection points were receiving the acid and how the flow was being diverted between them.
- **Wormhole Competition Analysis:** The primary analysis was done via CT scanning. The scans visualized the wormholes originating from each of the five injection points. This allowed the study of "wormhole competition" and confirmed that the VES helped create a more uniform and extensive network of flow channels compared to HCl alone.
- **Wormhole Parameter Calculation:** From the CT scans, key parameters like wormhole volume, length, and diameter were calculated to assess the diversion efficiency quantitatively.

2.3.4. Resources Exploited and Applied

- **Novel Multi-Point Core Holder:** This custom-built piece of equipment was the central resource for the study.
- **Complete Flooding System:** The system included the core holder, accumulators, an ISCO pump, pressure transducers, and a sample collector, all housed within an oven to maintain reservoir temperature.
- **Imaging and Visualization:** A CT scanner and PerGeos software were used for detailed 3D visualization and analysis of the complex wormhole structures.

Chapter III – Summary of Results, Exploitation, and Applications

This chapter summarizes the key research results from the experimental studies, highlighting their implications for industry and potential applications. It also addresses the limitations encountered and suggests future research directions.

3.1. Optimization of Injection Rates Using Carbonic Acid

Key Findings:

- **Optimal Injection Rate Determination:** Two models were employed to determine the optimum injection rate for carbonic acid in carbonate formations. Wang's model, based on experimental data, suggested an optimal rate of 2 cm^3/min, yielding the lowest pore volume to breakthrough (PVBT) of 21.9, as shown in Figure 6. Buijse and Glasbergen's semi-empirical model, which correlates PVBT with interstitial velocity, indicated an optimal interstitial velocity of 1 cm/min, corresponding to an injection rate of 1.7 cm^3/min (Figure 7). The latter model is considered more robust for predicting the true optimum PVBT because it relies on a broader range of experimental data.
- **Wormhole Morphology and Evolution:** Injection rate significantly influenced wormhole morphology and volume. At low injection rates (0.5 cm^3/min), branched At a low injection rate of 0.5 cm^3/min (Figure 9D), face dissolution did not occur due to carbonic acid's relatively slow reaction kinetics. However, this condition led to the formation of a branched wormhole, yielding the highest wormhole volume among the experiments. Increasing the injection rate slightly to 1 cm^3/min (Figure 9C) resulted in a notable loss of acid from the wormhole walls, leading to conical wormholes with multiple branches within the core. A dominant, less branched wormhole was formed, requiring a minimal pore volume for breakthrough at an intermediate injection rate of 2 cm^3/min (Figure 9B). This type of wormhole, known as a dominant wormhole, exhibited the lowest wormhole volume. Further increasing the injection rate to 5 cm^3/min (Figure 9A) resulted in the acid penetrating tiny pores, increasing surface area contact, and higher acid consumption. This condition led to ramified wormholes characterized by branched flow channels.
- **Petrophysical Property Alterations:** Carbonic acid injection resulted in significant changes in the petrophysical properties of Indiana limestone cores. While the final porosity consistently increased across all experiments, the lowest porosity change was observed at the optimal

injection rate, attributed to the formation of a single, straight wormhole. Importantly, the permeability became infinite after the wormhole was created, signifying a substantial enhancement in fluid flow pathways Figure 10.

- **Calcium Dissolution Efficiency:** Inductively Coupled Plasma (ICP) analysis showed that the injection rate directly affects calcium dissolution. Increasing the rate from 0.5 cm^3/min to 2 cm^3/min resulted in a significant increase in calcium concentration (from 2770 ppm to 7070 ppm), indicating optimal dissolution efficiency at 2 cm^3/min. Further increasing the rate to 5 cm^3/min led to a decrease in calcium concentration (5146 ppm), suggesting a less efficient reaction at higher rates.
- **Damköhler Number Analysis:** The study determined the optimum Damköhler number for carbonic acid to be 0.005, which is significantly lower than the established value of 0.29 for other acid systems Figure 8. This deviation highlights the unique reaction dynamics and weaker nature of carbonic acid compared to conventional acids like HCl.

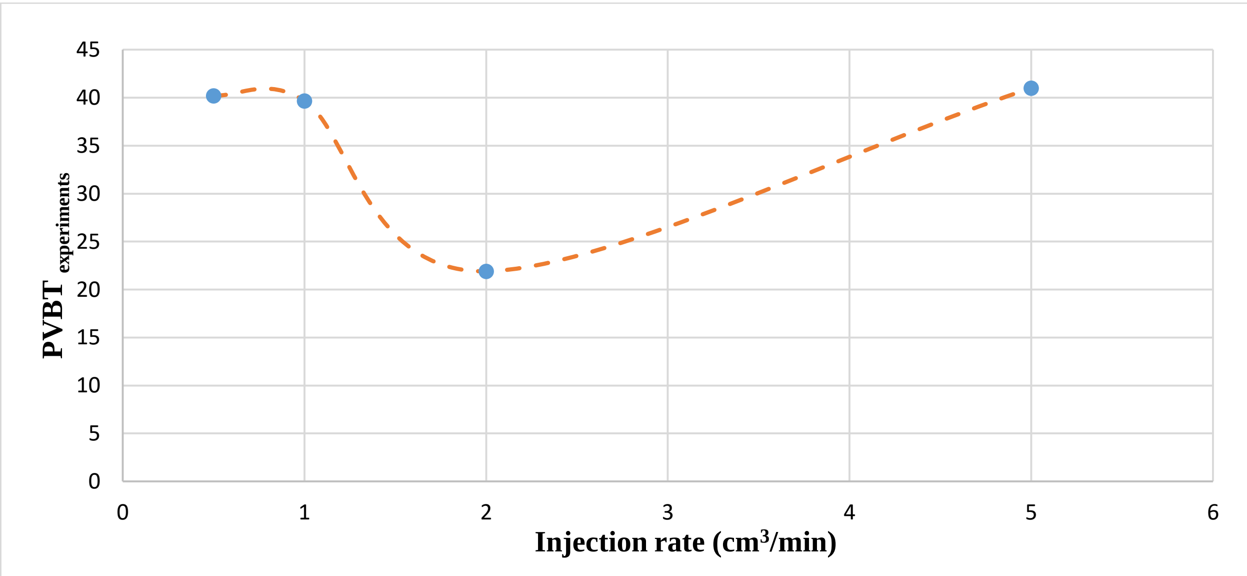


Figure 6: Experimental optimum injection rate graph

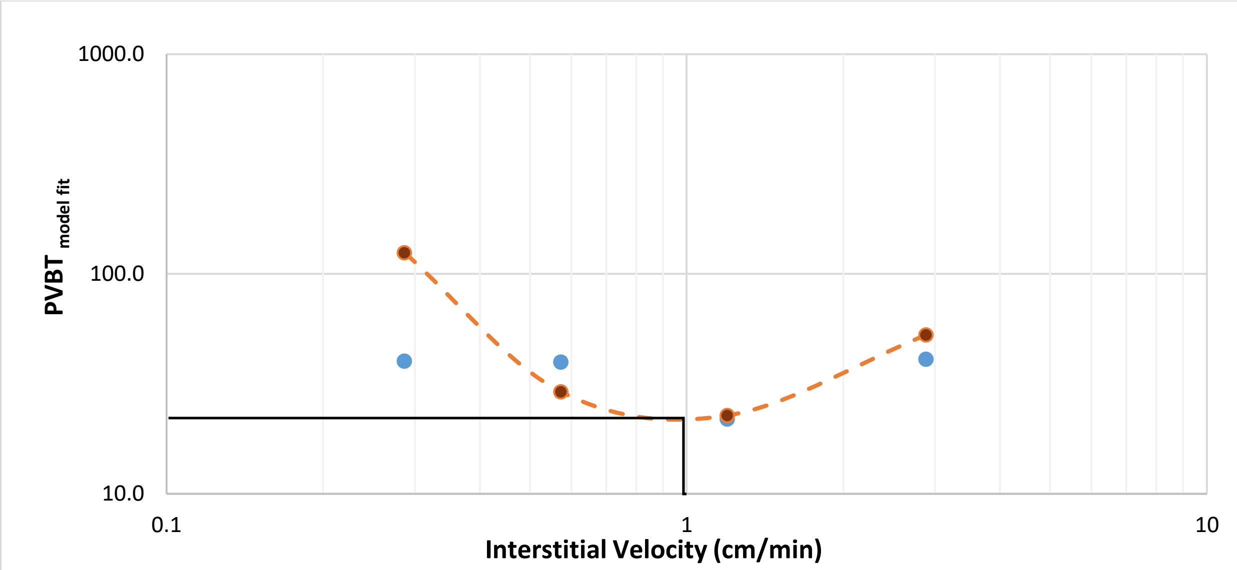


Figure 7 Optimum interstitial velocity based on the Buijse and Glasbergen model

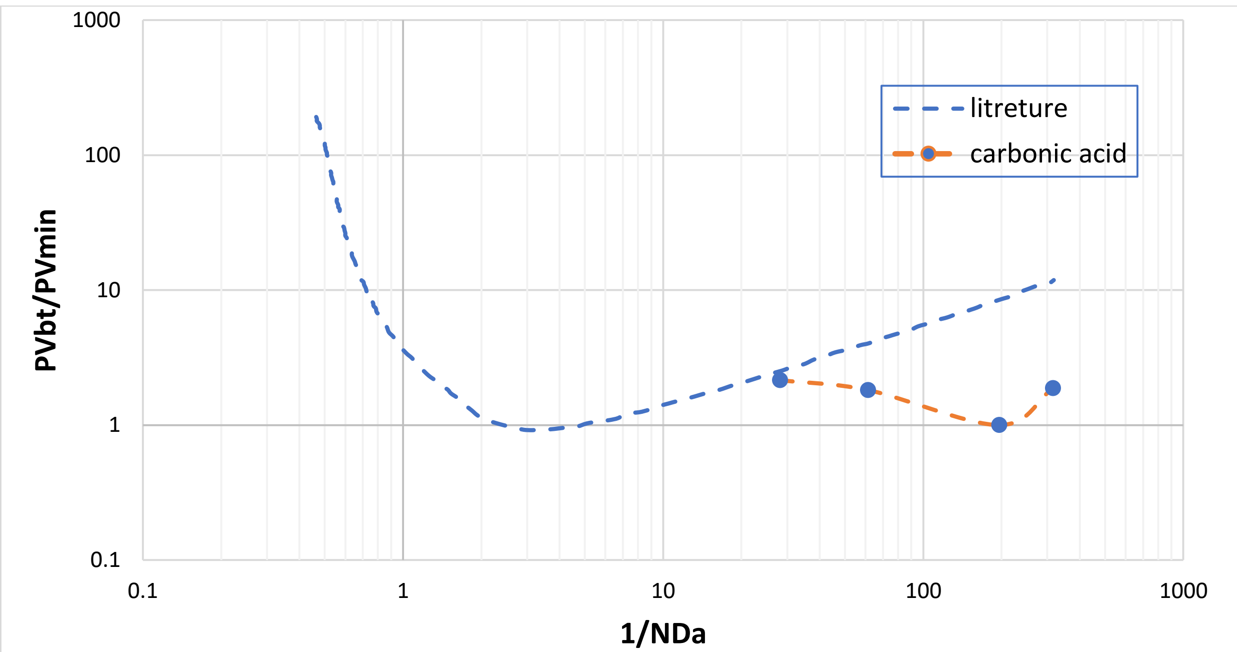
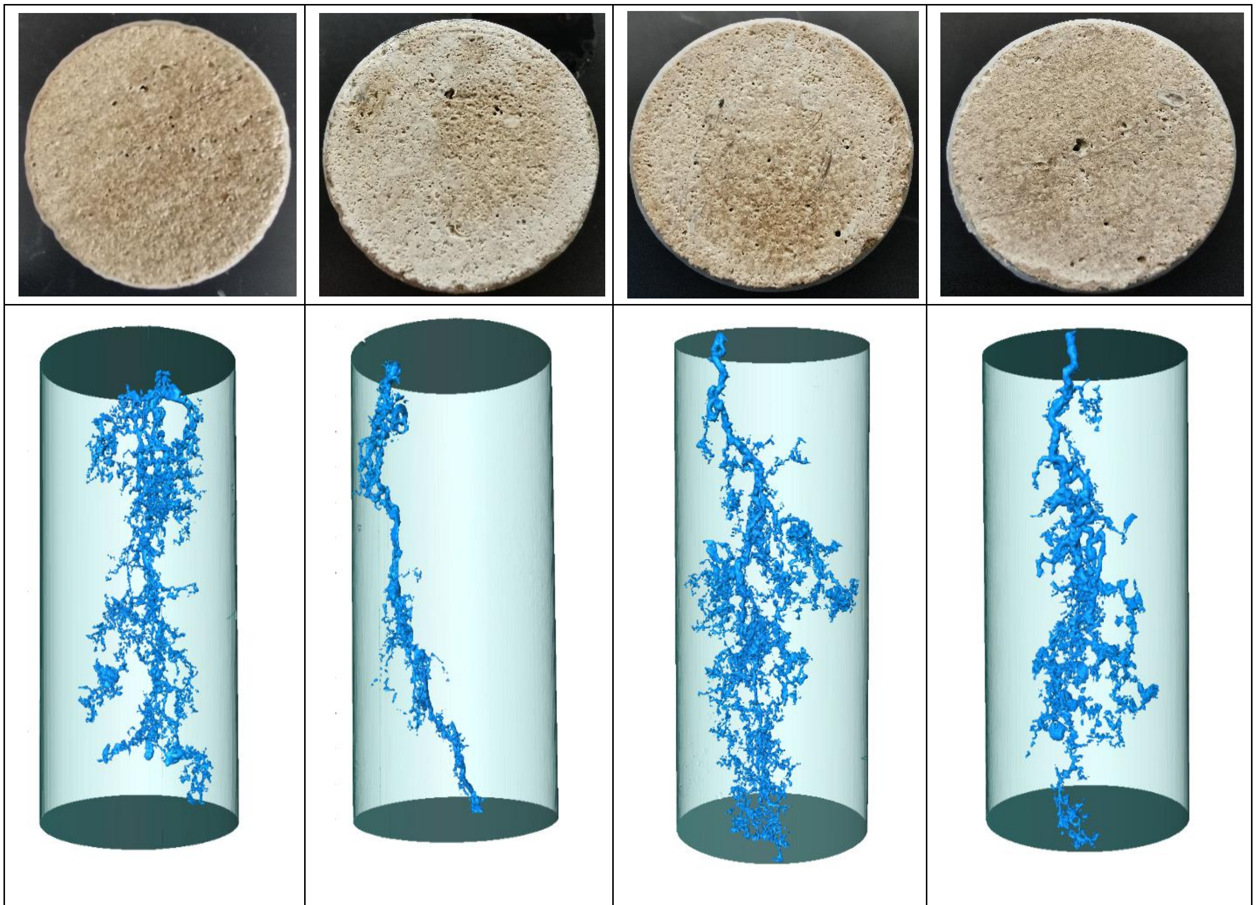


Figure 8: Plot the normalized number of pore volumes required to achieve a breakthrough against the reciprocal of the generalized Damköhler number of carbonic acid

Inlet face after core flooding



IR= 5 cm^3/min Wormhole radius = 1.56 mm	IR= 2 cm^3/min Wormhole radius = 1.025 mm	IR= 1 cm^3/min Wormhole raius = 1.575 mm	IR= 0.5 cm^3/min Wormhole radius = 1.735 mm
(A)	(B)	(C)	(D)

Figure 9 Wormhole shapes of single core flooding experiments where (A) IL1, (B) IL2, (C) IL3, (D) IL4

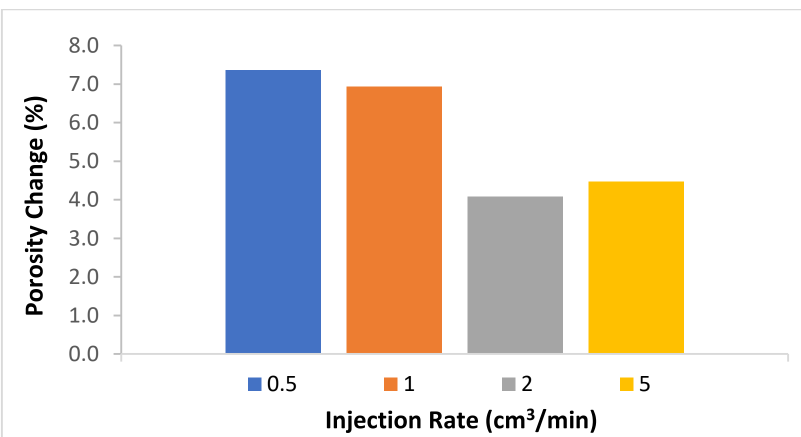


Figure 10: The porosity change due to different injection rates

3.2. Acid Diversion Using a Dual-Core Flooding System

Key Findings:

- **VES-Carbonic Acid System Effectiveness:** The integration of carbonic acid with viscoelastic surfactants (VES) significantly improved acid distribution in heterogeneous carbonate formations. Dual-core flooding experiments demonstrated that the VES-carbonic acid system effectively diverted acid flow, leading to more uniform treatment of both high- and low-permeability zones (Figure 16 and Figure 17), albeit requiring a longer time to achieve breakthrough than VES-hydrochloric acid systems (Figure 14 and Figure 15).
- **Rheological Behavior of VES:** Rheological tests on newly developed VES products, particularly FTS-20, revealed shear-thinning behavior and a significant increase in viscosity (up to 150 cP) at optimal $CaCl_2$ concentrations (10%), as shown in Figure 11. This micellar transition effect is crucial for blocking high-permeability channels and diverting acid to less permeable areas.
- **Comparison with Neat HCl:** In contrast to neat HCl, which preferentially flows into high-permeability zones, leaving low-permeability areas untreated Figure 13, the VES-enhanced systems (both HCl and carbonic acid) demonstrated superior diversion capabilities. The CT scan results confirmed the formation of single, similar-width wormholes in both low and high-permeability cores when VES was used, indicating effective acid placement.

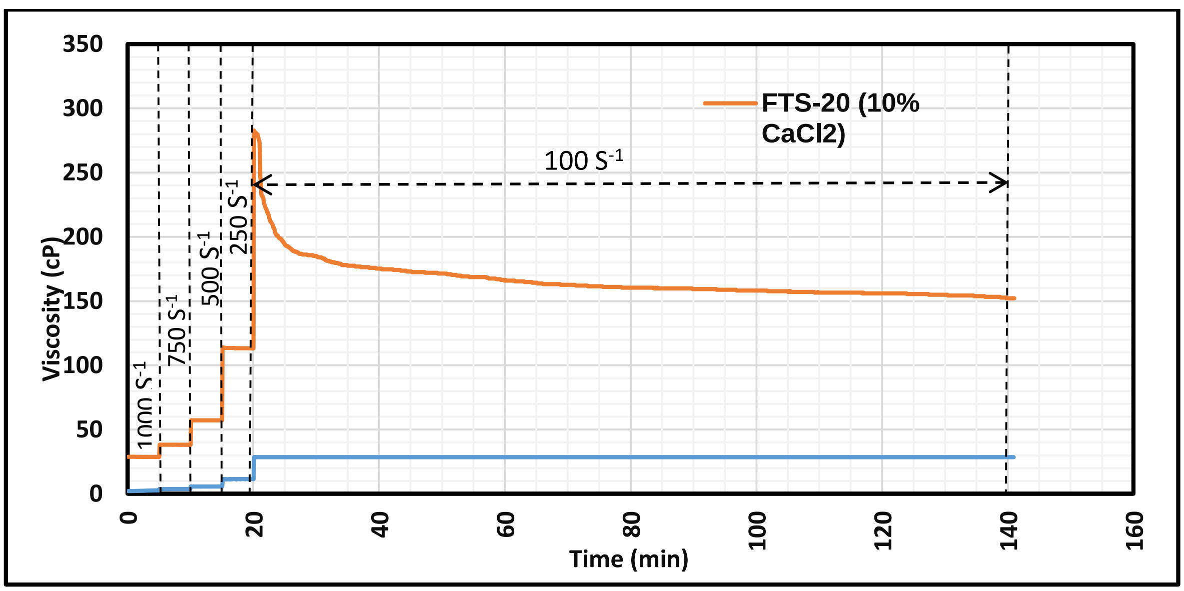


Figure 11 Viscosity as a function of time for FTS-20 at different CaCl2 concentrations under shear rate range of 1000 to 100 S-1 at 60 °C

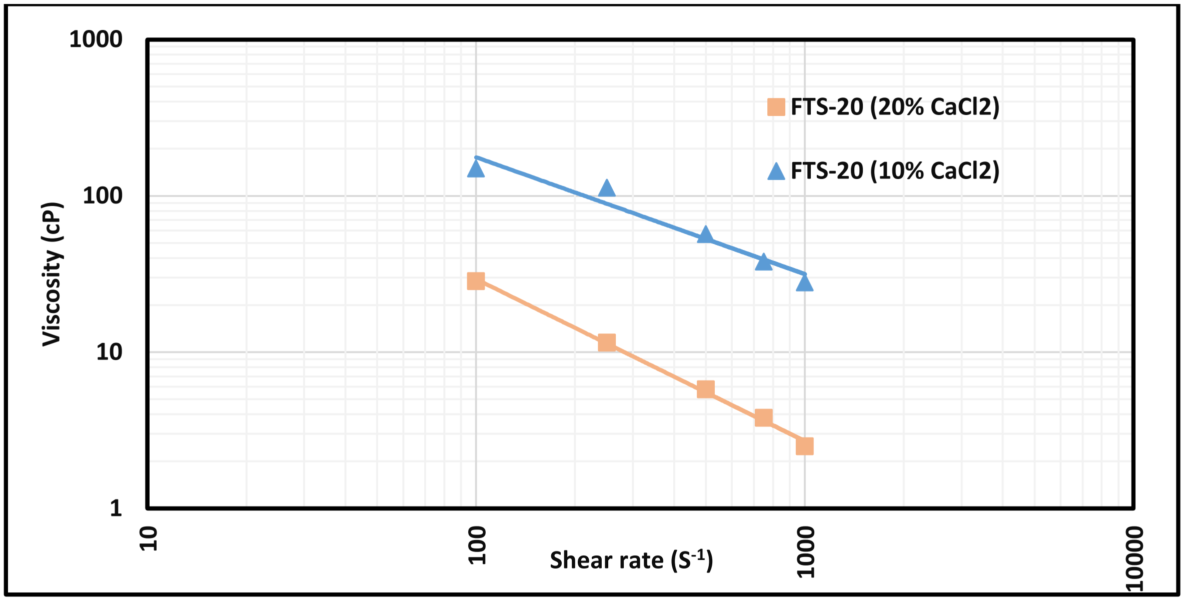


Figure 12: Viscosity as a function of shear rate for FTS-20 at different CaCl2 concentrations at 60° C

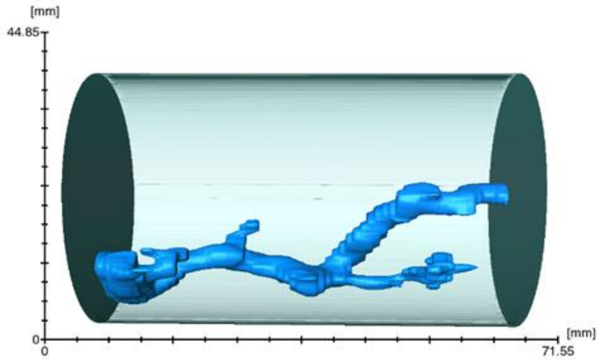


Figure 13: Wormholes generated during neat HCl acid injection in IL7 sample

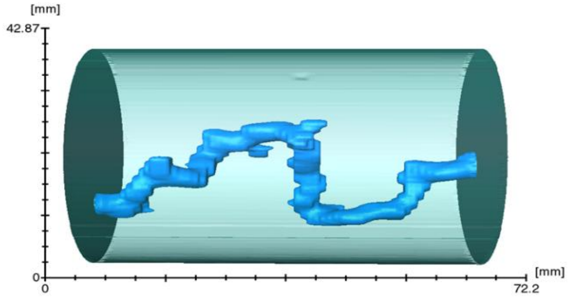


Figure 14 Wormholes generated during VES acid system injection in IL9 sample

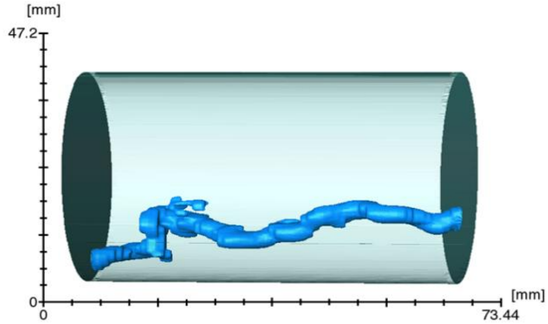


Figure 15 Wormholes generated during VES acid system injection in IL10 sample

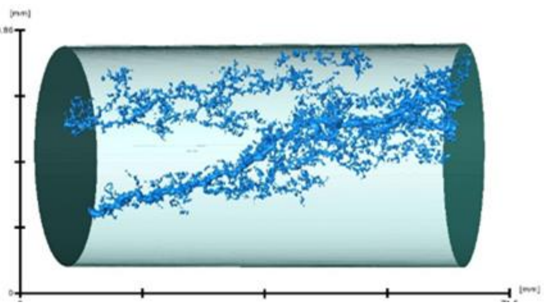


Figure 16 Wormholes generated during VES carbonic acid system injection in IL11 sample

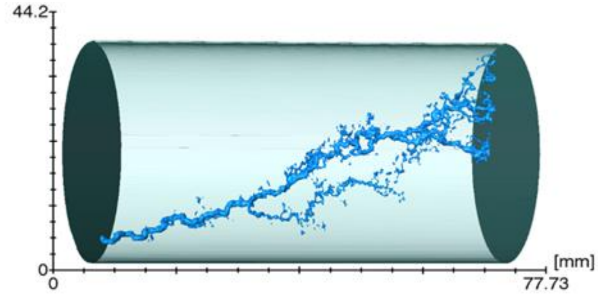


Figure 17 Wormholes generated during VES acid system injection in IL12 sample

3.3. Acid Diversion Using a Novel Single-Core Design

Key Findings:

- Multi-Point Injection System Validation: The novel single-core holder design with five injection points and two outlet lines proved effective in simulating and evaluating acid diversion in horizontal wells. This design enabled a more realistic assessment of the performance of chemical diverters in distributing acid across heterogeneous formations.
- Wormhole Propagation Control: The flooding outcomes from the four experiments using the novel multi-point injection technique yield significant insights into acid distribution and diversion performance during matrix acidizing in horizontal wells. Experiment 1 (IL1), which used only hydrochloric acid (HCl), showed limited diversion, resulting in wormholes on both sides of the sample, highlighting the need for improved acid placement strategies (Figure 18). Experiments 2 (IL2), Figure 19, and 3 (IL3), Figure 20, which used HCl with viscoelastic surfactants (VES), showed more successful diversion than the first experiment, as evidenced by higher wormhole volumes and longer lengths. Experiment IL4 (Figure 21) demonstrated the potential for improved diversion in heterogeneous reservoir conditions using two samples with different permeabilities.
- In experiments 3 and 4 (HCL with VES), wormhole propagation occurred on both sides due to the flow fluctuation. This phenomenon was attributed to a temporary viscosity-induced blockage. When the acid flows on one side, the acid-calcite reaction induces a structural transformation in the VES molecule from spherical to rod-shaped, leading to wormlike micelles. The viscosity increased locally due to this transformation, which created a temporary blockage. Consequently, the flow is redirected to the previously blocked side. This process

was repeated cyclically, alternating the flow on both sides. As a result, the wormhole was longer on both sides than in other experiments.

- The observed diversion enhancement in flooding experiments is due to the rheological behavior of the viscoelastic surfactant (VES) under the experimental conditions. We conducted rheological tests on the fluid at 60 °C and measured the viscosity of the acid-treated fluid at various shear rates. The results showed shear-thinning behavior, where viscosity decreased as the shear rate increased. This behavior is crucial because the viscosity increment at a low shear rate creates flow resistance in the high-permeability zone, which, in turn, redirects the flow to the low-permeability zone. The rheological tests confirmed that the VES produced a significant increase in viscosity, reaching 153 cP, validating the enhanced flow resistance and effective diversion it caused.
- Computed tomography (CT) scan results demonstrate the efficacy of the new multi-point injection technique for evaluating the diversion efficiency of specific chemicals during matrix acidizing in horizontal wells. The wormhole volumes of Samples IL2 and IL3 are much higher, suggesting improved diversion efficiency, particularly when using chemical diverters such as viscoelastic surfactants (VES). The results emphasize the importance of using modern CT scans to precisely assess acid-diversion schemes, leading to improved reservoir stimulation techniques and optimal hydrocarbon extraction.
- **Impact of Heterogeneity:** The study confirmed that wormhole initiation locations varied due to heterogeneity in formation. In all experiments, only two wormholes were formed among the five injection points, indicating that not all perforations in horizontal wells receive acid.

IL1 (12 in)	Volume fraction =0.018

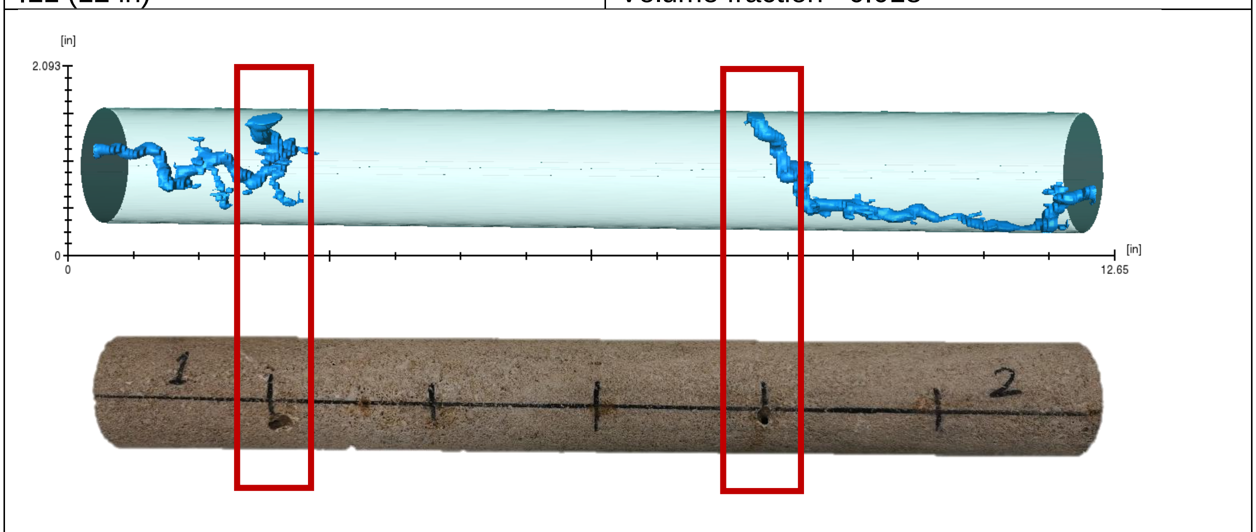


Figure 18: Wormholes generated during Experiment 1

IL2 (12 in)	Volume fraction = 0.030

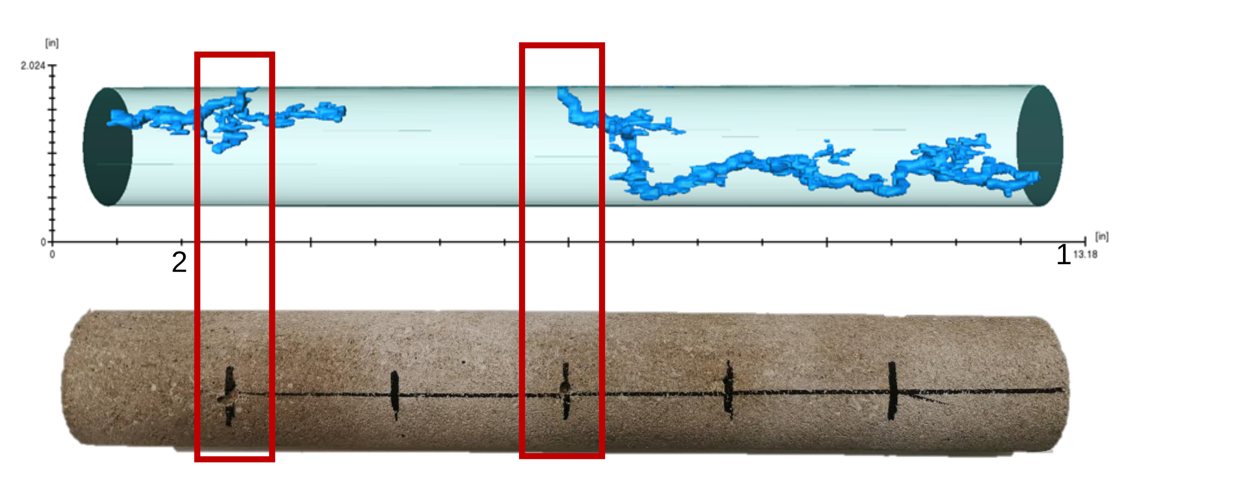


Figure 19: Wormholes generated during Experiment 2

IL3 (12 in)	Volume fraction = 0.034

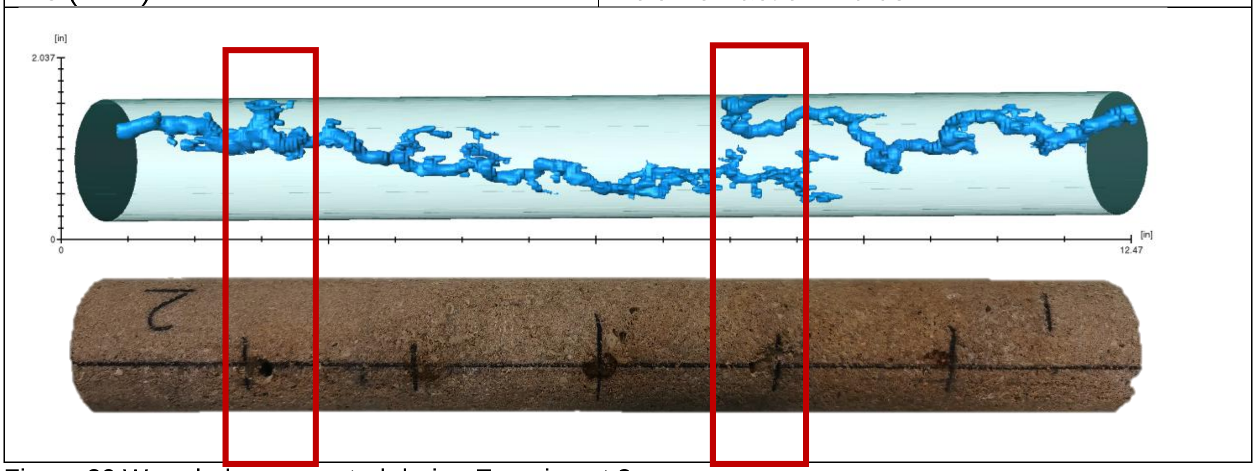


Figure 20 Wormholes generated during Experiment 3

IL4 (6 in) high permeability	IL5 (6 in) low permeability
Volume fraction = 0.024	Volume fraction = 0.025

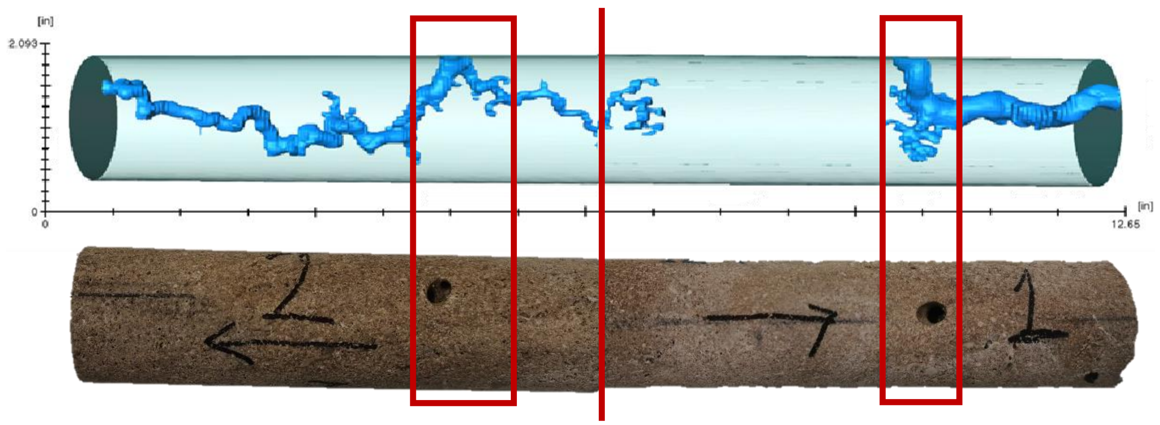


Figure 21: Wormholes generated during Experiment 4

3.4. Implications for Industry

Carbonic Acid as a Green Alternative: These findings establish the efficacy of carbonic acid as a green alternative to hydrochloric acid (HCl) for acidizing carbonate formations, addressing both environmental concerns and corrosion-related issues.

Acid diversion system: The combination of the VES-carbonic acid system improves acid distribution, especially in heterogeneous reservoirs.

Economic and Operational Advantages: Reduced consumption of conventional acid and enhanced diversion efficiency may result in lower operational costs and improved safety during well-stimulation operations.

Novel design: the core holder with 5 injection points helps understand acid diversion in a horizontal well and opens the window to identify the best chemical for optimal acid diversion.

Chapter IV: New Scientific Achievements

1- Introduction of carbonic acid as a matrix acidizing fluid for carbonate formation

This study experimentally introduced carbonic acid (H_2CO_3), prepared from a mixture of 30% CO_2 and 70% DI water, as an eco-friendly and less corrosive alternative to traditional acid for matrix acidizing in carbonate formation. Unlike previous studies that used salted water for carbonic acid preparation, this work used DI water to better control fluid composition and reaction behavior.

2- Identification of the optimum injection rate for carbonic acid in carbonate limestone.

The study determined the optimum injection rate of carbonic acid during matrix acidizing in carbonate formations. The study investigates different injection rates and their impact on wormhole formation, dissolution rate, and changes in petrophysical properties. Two models were used to determine the optimum injection rate: the Wang model and the Bujis & Glasbergen semi-empirical model approach, yielding results of 2 and 1.7 cm^3/min, respectively.

3- Identification of a new optimum Damköhler number for carbonic acid

While the standard literature Damkohler number introduced by Fredd and Fogler is 0.29, this study showed that the optimum Damkohler number is lower, around 0.005, proving the weak nature of carbonic acid.

4- Development and validation of a novel single-core holder design with five injection points.

A novel core flooding system was developed featuring five injection spots positioned perpendicular to the core samples, simulating perforations in a horizontal well. The new setup provides a more realistic evaluation of wormhole propagation and acid diversion efficiency in heterogeneous carbonate rocks. The research highlights how different acid systems influence the development and propagation of wormholes within the rock.

5- The first experimental study of acid diversion used carbonic acid with VES in a dual-core flooding system.

For the first time, this study introduced the combination of carbonic acid with viscoelastic surfactant for acid diversion in heterogeneous carbonate formation. Diversion efficiency was evaluated using a dual-core flooding system. The experiments confirmed the performance of the VES carbonic acid system and its effectiveness in acid distribution and in redirecting acid flow from high- to low-permeability zones.

Chapter V: List of publications and presentations

Publications by the Candidate:

1. Abdulameer Almalichy, Usama Alameedy, and Zoltan Turzo, CARBONATE ROCK MATRIX ACIDIZING: A REVIEW OF ACID SYSTEMS AND REACTION MECHANISMS, XXV Spring Wind Conference, 26/05/2022.
2. Abdulameer Almalichy, Zoltan Turzo, Murtada Aljawad, Ahmed Alyasri, A Novel Approach to Assess Acid Diversion Efficiency in Horizontal Wells – Scientific report -2025 https://doi.org/10.1038/s41598-024-84671-y
3. Abdulameer Almalichy, Murtada Aljawad, Ahmed Alyasri, A novel core flooding system for simulating acid diversion in horizontal wells – Patent submission- USPTO- application No.18/946,725
4. Abdulameer Almalichy, Zoltan Turzo, Murtada Aljawad, Ahmed Alyasri, A Study of The Optimum Injection Rate of Carbonic Acid During Matrix Acidizing of Carbonate Reservoirs: Implications For Reducing CO2 Emissions- Heliyon- 2024- https://doi.org/10.1016/j.heliyon.2024.e39955
5. Abdulameer Almalichy, Zoltan Turzo, The Impact of Carbonic Acid on Porosity and Pore Structure During Matrix Acidizing of Carbonate Reservoirs: Implications for Reducing CO2 Emissions, Civil and Environmental Engineering Reports, 2025 DOI: https://doi.org/10.59440/ceer/200053

Conference Presentations:

1. Carbonate Rock Matrix Acidizing: A Review Of Acid Systems And Reaction Mechanisms, Spring Wind Conference 2022, University of Pecs, 07/05/2022
2. Matrix Acidizing in a tight oil reservoir, Forum of Doctoral Students conference, University of Miskolc, 17/11/2022
3. Assessing Petrophysical Changes During Carbonic Acid Matrix Acidizing- Multiscience - XXXVII. Microcad International Multidisciplinary Scientific Conference- University of Miskolc- 30-31 May 2024
4. The Impact of Carbonic Acid On Porosity During Matrix Acidizing Of Carbonate Reservoirs: Implications For Reducing Co2 Emissions- XXIV Conference of Ph.D. Students and Young Scientists- Wroclaw, Poland on October 23-25, 2024