Geosciences and Engineering, Vol. 13, No. 2 (2025), pp. 66–75.
https://doi.org/10.33030/geosciences.2025.02.005

INFLUENCE OF INJECTION RATE ON WORMHOLE MORPHOLOGY IN MATRIX ACIDIZING USING CARBONIC ACID

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Abstract: This study examines the effect of varying injection rates on wormhole formation during matrix acidizing using a carbonic acid solution (30% CO_2 + 70% deionized water). Injection rates of 0.2, 0.5, and 1 cm^3/min were tested, and the resulting wormhole structures were visualized using CT scanning. Results show that lower injection rates produce single, more efficient wormholes with minimal branching, while higher rates generate more branched, less efficient structures. Optimizing the injection rate is key to achieving effective wormhole formation, which can enhance flow in carbonate reservoirs.

Keywords: *carbonic acid, wormhole, computed tomography scan, matrix acidizing*

1. INTRODUCTION

Recent advancements in CO_2 utilization have expanded its potential beyond traditional applications like enhanced oil recovery (EOR) and carbon capture and storage (CCS). One emerging application is using carbonic acid, derived from CO_2 and water, as a stimulation fluid for carbonate reservoirs. This method reduces greenhouse gas emissions and addresses tubular corrosion commonly associated with hydrochloric acid (HCl) usage. Carbonic acid offers a more sustainable and eco-friendly alternative for well-stimulation without compromising efficiency (Almalichy et al., 2024; Al-Yaseri et al., 2023; Ma et al., 2021).

Matrix acidizing, a widely used technique, enhances well productivity by injecting acid solutions below the formation's fracture pressure to remove formation damage and create flow channels known as "wormholes" (Alameedy et al., 2023; Almalichy et al., 2022). While HCl has been the primary acid in use since the 1890s due to its effectiveness in dissolving carbonate formations, it presents challenges such as high corrosivity, rapid reaction rates in high-temperature and high-pressure environments, and the need for costly corrosion inhibitors (Chacon and Pournik, 2022). As a result, alternative acids with slower reaction rates and reduced corrosivity are being sought (Rodrigues et al., 2021) to stimulate the heterogeneous carbonate revervoir(Mohammed and Velledits, 2024).

Organic acids, such as methanesulfonic acid (MSA) and acetic acid, are increasingly considered practical substitutes for conventional acid systems in matrix acidizing. MSA is notable for its reduced reactivity relative to hydrochloric acid (HCl), an attribute assigned to its weakened hydrogen ion (H^+) activity coefficient and elevated pKa value. These properties markedly reduce the acid's reaction rate with carbonate formations, facilitating deeper reservoir penetration. The reduced reactivity is beneficial for forming efficient wormholes, essential for increasing permeability and optimizing hydrocarbon flow pathways (Ortega, 2015; Shank and McCartney, 2013).

Like other weak acids such as formic acid, Acetic acid shows slower reaction kinetics than stronger acids such as HCl. This reduced reactivity facilitates a regulated acid-rock interaction, enabling the acid to penetrate deeper into the formation. The outcome is a more consistent stimulation and the possibility of enhanced acid infiltration into the reservoir matrix, which is especially advantageous for reservoirs characterized by significant heterogeneity or complex conditions. These organic acids provide customized solutions for effective stimulation while reducing unwanted near-wellbore reactions (Al-Douri et al., 2013; Chang et al., 2008).

The different retarded acid systems, including gelled acids, in-situ gelled acids, and emulsified acids, were developed and published as novel means of controlling acid reactivity for the stimulation of carbonate reservoirs. These are specially designed to retard the acid-rock reaction rate to improve the depth and uniformity of acid penetration and minimize the problem of premature acid spending near the wellbore. Gelled acids are among the most effective techniques. Gelled systems improve acid placement by reducing fluid loss and providing better coverage in the formation due to increased acid viscosity(AlOtaibi et al., 2020). This enhanced viscosity plays a vital role in overcoming problems in heterogeneous-permeability formations where conventional acid treatments often fail. Conventional acids tend to bypass into high-permeability zones and avoid areas of low permeability. Gelled acids can compensate for this deficiency by offering a more uniform distribution of the acid, with delivery into low-permeability zones that otherwise would not have been treated. Moreover, the high-viscosity nature of gelled acids prevents leak-off into the surrounding formation, which maintains the acid strength and allows deeper and more effective wormholes. Therefore, the gelled acid systems are perfect for stimulating carbonate reservoirs with dominantly complex rock properties such as variable porosity and permeability (Ratnakar et al., 2012).

Apart from their role in regulating reactivity and improving distribution, gelled acids contribute to operational efficiency and economy. Indeed, they require a smaller volume of acid to achieve similar or improved performances compared with the conventional acid systems. This, in turn, reduces the overall consumption of treatment fluids. They can minimize near-wellbore damage and provide even stimulation across the formation, translating this into higher well productivity and extended life of the treatment(Lynn and Nasr-El-Din, 2001; Zakaria and Nasr-El-Din, 2016).

Emulsified acids, comprising finely dispersed hydrochloric acid (HCl) droplets within a continuous oil phase, effectively regulate acid-rock interactions during matrix acidizing operations. The distinctive composition of these emulsions markedly inhibits the reaction between the acid and the carbonate rock, facilitating deeper penetration of the acid into the reservoir before the reaction. This regulated reactivity is essential for enhancing acid distribution and attaining more consistent stimulation. Surfactants are necessary for preserving the stability of emulsified acids by facilitating the formation and stabilization of the emulsion structure. Surfactants effectively control acid release at the rock surface by capturing the acid droplets within the oil phase. This mechanism decreases acid consumption near the wellbore. It mitigates premature acid expenditure, thereby facilitating a larger volume of acid to penetrate deeper into the formation, where it can generate effective wormholes. (Al-Anazi et al., 1998; Maheshwari et al., 2014).

Besides effectiveness related to the improvement of wormhole formation, several advantages of emulsified acid are associated with its own nature. The oil phase in the emulsion may act like a seal, significantly reducing leakoff of the acid into the formation matrix and preserving the acid for intended reaction zones. This characteristic is especially welcome in reservoirs with sharp permeability contrasts, where conventional acid systems often fail to yield balanced stimulation. Emulsified acids enable more resource efficiency and better treatment outcomes by reducing the active agent loss to a minimum and optimally applying the acid. Moreover, the tunable properties of the emulsified acid systems enable modifications in properties for matching conditions in specific reservoirs. The type of surfactant, formulation of the oil phase, and acid concentration can be changed in order to optimally develop the emulsion for various operational conditions. The versatility of emulsified acids makes them amenable to addressing most of the problems associated with heterogeneous carbonate formations (Buijse and van Domelen, 1998; Crowe and Miller, 1974).

Emulsified acids economically provide a means of cost savings through the reduction of the total amount of acid required for effective stimulation. Their capability to increase the penetration depth, reduce near-wellbore acid lost, and improve treatment efficiency gives them long-term production benefits, thus making them an important component in acidizing today (Adewunmi et al., 2022).

Chelating agents such as ethylenediaminetetraacetic acid (EDTA) and nitrilotriacetic acid (NTA) have been extensively studied to enhance deep acid penetration and promote uniform distribution within carbonate formations. These chemicals form very stable complexes with calcium ions; therefore, they offer very good control of the acid reaction rate and a drastic reduction of excessive acid consumption near the well-bore. This controlled reaction mechanism provides a particular advantage in applications to high-temperature carbonate reservoirs, where the use of conventional acidizing methods is commonly limited. (Frenier et al., 2000; Yan et al., 2019).

Foamed acid systems, prepared conventionally by adding nitrogen gas to hydrochloric acid, represent an innovative and efficient technology in acid reactivity control for carbonate reservoirs. The entrapment of gas within the acid reduces the contact between the acid and the rock surface while significantly reducing the overall reaction rate. This reactivity control will allow deeper and more efficient wormhole formation with less excessive acid consumption and, therefore, a more economical process (Al-Nakhli et al., 2020, 2021). Besides, foamed acids are very effective against the numerous problems of heterogeneous carbonate formations. The specific structure of the foamed acids allows for better distribution of the acid in rocks with different permeabilities, thus ensuring more balanced stimulation of the formation. This homogeneity enhances the depth of acid penetration, even at low injection rates, which is of particular help in formations where uneven acid distribution or near-wellbore spending may reduce the effectiveness of the treatment. Foamed acids, therefore, besides helping to improve stimulation efficiency, also contribute to well productivity in the long term (Bernadiner et al., 1992; Cheng et al., 2002; Zerhboub et al., 1994). This approach has received growing interest in the last decade due to its promising potential for better optimizing acidizing treatments in heterogeneous reservoir environments (Cao et al., 2021).

Numerous studies have investigated wormhole formation using strong acids such as HCL, organic acid, gelled acid, emulsified acid, and chelating acid systems. This study investigates the use of carbonic acid for carbonate reservoir stimulation, focusing on the impact of varying injection rates on wormhole formation. A carbonic acid solution (30% CO_2, 70% deionized water) was injected at rates of 0.2, 0.5, and 1 cm^3/min, with the resulting wormhole structures visualized through CT scanning. Results show that lower injection rates produce more efficient, single wormholes with minimal branching, while higher rates result in more branched, less effective structures. Optimizing the injection rate is essential for improving wormhole efficiency and enhancing flow in carbonate reservoirs.

2. MATERIALS AND METHODS

2.1. Experimental procedure

The experimental process (Fig. 1) began by measuring porosity using a helium porosimeter and estimating permeability with Autoscan. The core sample was dried at 100°C, vacuumed for three hours, and saturated with fresh water at 2000 psi for 24 hours. Core flooding was then performed, and differential pressure (DP) and pore volume were recorded for breakthrough (PVBT). After flooding, the core was dried, porosity was re-measured, and a CT scan was used to visualize the wormhole.

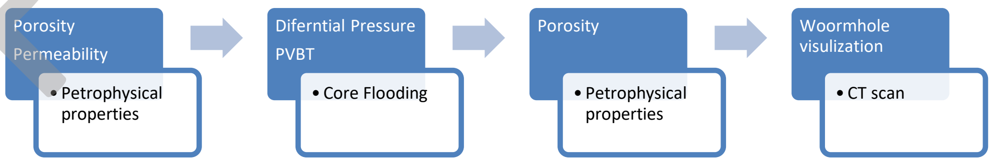


Figure 1
The experimental workflow

2.2. Investigated samples

Three Indiana limestone core samples (2.5 inches long, 1.5 inches in diameter) were used in this study. Initial porosity, measured with helium porosimetry (AP-608) (Table 1). Permeability ranged from 3 to 7 mD. XRD analysis confirmed that the limestone consists entirely of calcite. Each core was wrapped in a shrink tube to prevent cross-flow.

Table 1

Core sample characteristics and properties

Core No.	IR (cm^3/min)	Porosity (%)	Permeability (mD)
IL8	0.2	14.91	3.4
IL12	0.5	15.32	7
IL10	1	15.17	4

2.3. Core flooding

The core flooding experiments involved injecting carbonic acid into Indiana limestone samples to study their behavior under high pressure and temperature. The core samples were housed in a Hastelloy core holder, with an ISCO pump controlling the injection rates of carbonic acid at 0.2, 0.5, and 1 cm^3/min. Before the experiments, the core was sealed, loaded, and subjected to 3,500 psi and 2,000 psi confining and back pressures, respectively. Fresh water was initially injected at varying flow rates to measure the core's permeability. The process was stopped when the acid breakthrough occurred.

2.4. Computed tomography scan

CT scanning uses X-rays to create 2D images, forming a 3D model of the rock. It helps analyze porosity, permeability, and pore structure (Al-Marzouqi, 2018). After flooding, CT scans visualized wormholes, with their volumes estimated through software analysis

4. RESULTS

The core flooding experiments showed significant changes in porosity and permeability across the samples (Fig. 2). Sample IL8, subjected to a 0.2 cm^3/min injection rate, had an initial porosity of 14.91%, which increased to 16.01%. The permeability rose from 3.4 mD to infinity, indicating a substantial increase in fluid flow capacity. Similarly, Sample IL12, with an injection rate of 0.5 cm^3/min, showed an increase in porosity, from 15.32% to 16.05%, while its permeability increased from 7 mD to infinity. Sample IL10, injected at a higher rate of 1 cm^3/min, experienced porosity rising from 15.17% to 16.27%, with its permeability reaching infinity. This consistent increase in porosity shows that the injection process was quite effective for pore space enhancement in each of these samples, which can lead to a substantial increase in fluid flow and permeability. The wormhole formation is an important factor in enhancing fluid flow pathways in rock samples. The wormhole formation results derived from core flooding experiments conducted highlight how variations in injection rates may cause wide differences in the extent of the formation and the complexities of the formed wormhole networks. Sample 8 had the lowest injection rate of 0.2 cm^3/min and presented a wormhole volume fraction of 0.74%, indicating a more concentrated network that is less branched.

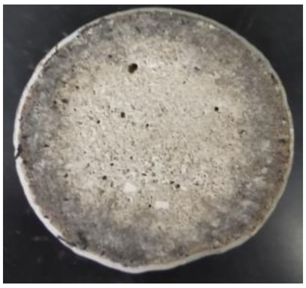
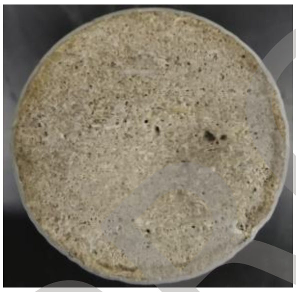
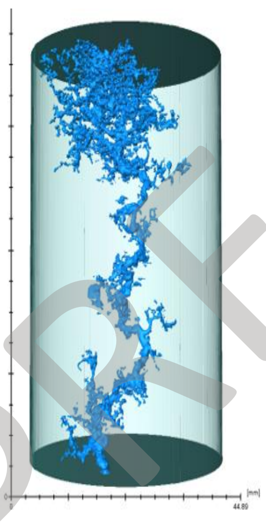
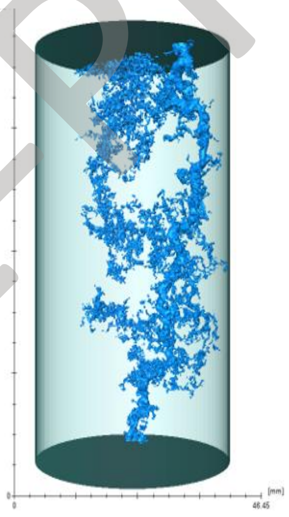
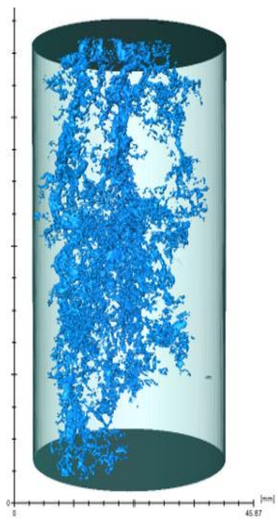
Inlet face after core flooding		
		
		
IR= 0.2 cm^3/min	IR= 0.5 cm^3/min	IR= 1 cm^3/min
(A)	(B)	(C)

Figure 2

Wormhole of single core flooding experiments, (A) IL8 (B) IL12 (C) IL10

Sample 10 was treated with the highest injection rate of 1 cm^3/min and developed the most in wormhole extent, with a volume fraction of 1.65%. It was characterized by highly branched wormholes all over the core, indicating aggressive fluid penetration. Sample 12, with the middle range injection rate of 0.5 cm^3/min, showed a moderately higher wormhole volume fraction of 1.08% with a relatively well-balanced distribution in the wormhole network. These changes represent that with the increase in injection rates, more complicated and highly expanded wormhole structures could be developed, which also coincides with the change rule of permeability and porosity.

5. Discussion and Conclusions

The obtained results of core flooding experiments are revealing and mightily informative about the effect of carbonic acid injection into Indiana limestone under high-pressure-high-temperature conditions. The experiments carried out lead to the interpretation that the injection rate largely influences the injected core samples in porosity, permeability, and hence in wormhole formation. Higher injection rates, such as in Sample 10, created incredibly complex and extensive wormhole networks, thus resulting in large increases in permeability. The infinite permeability values for all the samples after flooding reflect this increase, showing that the wormholes greatly enhance the pathways for fluid flow. The porosity increased in all samples, which directly correlates with the formation of wormholes, contributing to the overall void space within the rocks. Higher wormhole volume fractions observed for samples with higher injection rates reinforce this relationship since more aggressive acid injection promotes more aggressive rock dissolution and wormhole development.

The experiments have demonstrated that both higher and lower rates of carbonic acid injection significantly enhance porosity and permeability in Indiana limestone. However, the lower injection rate resulted in the formation of a more dominant and less branched wormhole, making it the more favorable injection rate. This will be important in understanding the behavior of carbonate reservoirs during the acid flooding process and could guide the optimization strategies in the stimulation of reservoirs and enhanced oil recovery operations.

References

Adewunmi, A. A., Solling, T., Sultan, A. S., & Saikia, T. (2022). Emulsified acid systems for oil well stimulation: A review. *Journal of Petroleum Science and Engineering*, *208*, 109569. https://doi.org/10.1016/j.petrol.2021.109569

Alameedy, U., Al-Haleem, A., Al-Saedi, A., Kadhim, H., & Khan, D. (2023). An experimental study of the effects of matrix acidising on the petrophysical characteristics of carbonate formation. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.04.128

Al-Anazi, H. A., Nasr-El-Din, H. A., & Mohamed, S. K. (1998, February 18). *Stimulation of Tight Carbonate Reservoirs Using Acid-in-Diesel Emulsions: Field Application*. SPE Formation Damage Control Conference. https://doi.org/10.2118/39418-MS

Al-Douri, A. F., Sayed, M. A., Nasr-El-Din, H. A., & Aften, C. (2013, April 8). *A New Organic Acid To Stimulate Deep Wells in Carbonate Reservoirs*. SPE International Symposium on Oilfield Chemistry. https://doi.org/10.2118/164110-MS

Almalichy, A., Aljawad, M. S., Turzo, Z., & Al-Yaseri, A. (2024). A study of the optimum injection rate of carbonic acid during matrix acidizing of carbonate reservoirs: Implications for reducing CO2 emissions. *Heliyon*, *10*(21), e39955. https://doi.org/10.1016/j.heliyon.2024.e39955

Almalichy, A., Turzó, Z., & Alameedy, U. (2022). *Carbonate Rock Matrix Acidizing: A Review of Acid Systems and Reaction Mechanisms*.

Al-Marzouqi, H. (2018). Digital Rock Physics: Using CT Scans to Compute Rock Properties. *IEEE Signal Processing Magazine*, *35*(2), 121–131. https://doi.org/10.1109/MSP.2017.2784459

Al-Nakhli, A., Gizani, M., Baiz, A., & Yami, M. (2021, December 15). *An Innovative Acid Diversion Using In-Situ Foam Generation: Experimental and Successful Field Application*. SPE Middle East Oil & Gas Show and Conference. https://doi.org/10.2118/204879-MS

Al-Nakhli, A., Zefzafy, I., Ahmed, D., & Kharrat, W. (2020, November 9). *A Novel Approach to Improve Acid Diversion Utilizing In-Situ Foam Generating Fluids*. Abu Dhabi International Petroleum Exhibition & Conference. https://doi.org/10.2118/203330-MS

AlOtaibi, F., Dahlan, M., Khaldi, M., AlGhamdi, A., & Al-Hulail, I. (2020, February 12). *Evaluation of Inorganic-Crosslinked-Based Gelled Acid System for High-Temperature Applications*. SPE International Conference and Exhibition on Formation Damage Control. https://doi.org/10.2118/199258-MS

Al-Yaseri, A., Al-Mukainah, H., Yekeen, N., & Al-Qasim, A. S. (2023). Experimental investigation of hydrogen-carbonate reactions via computerized tomography: Implications for underground hydrogen storage. *International Journal of Hydrogen Energy*, *48*(9), 3583–3592. https://doi.org/10.1016/j.ijhydene.2022.10.148

Bernadiner, M. G., Thompson, K. E., & Fogler, H. S. (1992). Effect of Foams Used During Carbonate Acidizing. *SPE Production Engineering*, *7*(04), 350–356. https://doi.org/10.2118/21035-PA

Buijse, M. A., & van Domelen, M. S. (1998, February 18). *Novel Application of Emulsified Acids to Matrix Stimulation of Heterogeneous Formations*. SPE Formation Damage Control Conference. https://doi.org/10.2118/39583-MS

Cao, C., Zhou, F., Cheng, L., Liu, S., Lu, W., & Wang, Q. (2021). A comprehensive method for acid diversion performance evaluation in strongly heterogeneous carbonate reservoirs stimulation using CT. *Journal of Petroleum Science and Engineering*, *203*, 108614. https://doi.org/10.1016/j.petrol.2021.108614

Chacon, O. G., & Pournik, M. (2022). Matrix Acidizing in Carbonate Formations. *Processes*, *10*(1), Article 1. https://doi.org/10.3390/pr10010174

Chang, F. F., Nasr-El-Din, H. A., Lindvig, T., & Qiu, X. W. (2008, September 21). *Matrix Acidizing of Carbonate Reservoirs Using Organic Acids and Mixture of HCl and Organic Acids*. SPE Annual Technical Conference and Exhibition. https://doi.org/10.2118/116601-MS

Cheng, L., Kam, S. I., Delshad, M., & Rossen, W. R. (2002). Simulation of Dynamic Foam-Acid Diversion Processes. *SPE Journal*, *7*(03), 316–324. https://doi.org/10.2118/79639-PA

Crowe, C. W., & Miller, B. D. (1974, May 15). *New, Low-Viscosity Acid-In-Oil Emulsions Provide High Degree Of Retardation At High Temperature*. SPE Rocky Mountain Regional Meeting. https://doi.org/10.2118/4937-MS

Frenier, W. W., Wilson, D., Crump, D., & Jones, L. (2000, October 1). *Use of Highly Acid-Soluble Chelating Agents in Well Stimulation Services*. SPE Annual Technical Conference and Exhibition. https://doi.org/10.2118/63242-MS

Lynn, J. D., & Nasr-El-Din, H. A. (2001, February 13). *A core based comparison of the reaction characteristics of emulsified and in-situ gelled acids in low permeability, high temperature, gas bearing carbonates*. SPE International Symposium on Oilfield Chemistry. https://doi.org/10.2118/65386-MS

Ma, L., Fauchille, A.-L., Ansari, H., Chandler, M., Ashby, P., Taylor, K., Pini, R., & Lee, P. D. (2021). Linking multi-scale 3D microstructure to potential enhanced natural gas recovery and subsurface CO2 storage for Bowland shale, UK. *Energy & Environmental Science*, *14*(8), 4481–4498. https://doi.org/10.1039/D0EE03651J

Maheshwari, P., Maxey, J., & Balakotaiah, V. (2014, November 10). *Simulation and Analysis of Carbonate Acidization with Gelled and Emulsified Acids*. Abu Dhabi International Petroleum Exhibition and Conference. https://doi.org/10.2118/171731-MS

Mohammed, A., & Velledits, F. (2024). Microfacies impacts on reservoir heterogeneity of early Cretaceous Yamama carbonate reservoir in South Iraq. *Scientific Reports*, *14*(1), 24184. https://doi.org/10.1038/s41598-024-74640-w

Ortega, A. (2015). *Acidizing High-Temperature Carbonate Formations Using Methanesulfonic Acid* [Thesis]. https://oaktrust.library.tamu.edu/handle/1969.1/155026

Ratnakar, R. R., Kalia, N., & Balakotaiah, V. (2012, May 14). *Carbonate Matrix Acidizing with Gelled Acids: An Experiment-Based Modeling Study*. SPE International Production and Operations Conference & Exhibition. https://doi.org/10.2118/154936-MS

Rodrigues, M. A. F., Arruda, G. M., da Silva, D. C., da Costa, F. M. F., de Brito, M. F. P., Antonino, A. C. D., & Wanderley Neto, A. de O. (2021). Application of nonionic surfactant nonylphenol to control acid stimulation in carbonate matrix. *Journal of Petroleum Science and Engineering*, *203*, 108654. https://doi.org/10.1016/j.petrol.2021.108654

Shank, R. A., & McCartney, T. R. (2013, March 17). *Synergistic and Divergent Effects of Surfactants on the Kinetics of Acid Dissolution of Calcium Carbonate Scale*. CORROSION 2013. https://dx.doi.org/

Yan, Y., Xi, Q., Una, C., He, B., Wu, C., & Dou, L. (2019). A novel acidizing technology in carbonate reservoir: In-Situ formation of CO2 foamed acid and its self-diversion. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *580*, 123787. https://doi.org/10.1016/j.colsurfa.2019.123787

Zakaria, A. S., & Nasr-El-Din, H. A. (2016). A Novel Polymer-Assisted Emulsified-Acid System Improves the Efficiency of Carbonate Matrix Acidizing. *SPE Journal*, *21*(03), 1061–1074. https://doi.org/10.2118/173711-PA

Zerhboub, M., Ben-Naceur, K., Touboul, E., & Thomas, R. (1994). Matrix Acidizing: A Novel Approach to Foam Diversion. *SPE Production & Facilities*, *9*(02), 121–126. https://doi.org/10.2118/22854-PA