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Multi-Parameter Experimental Investigation on the Characteristics of Acidizing Effectiveness in High-Temperature Carbonate Formation

Zhiheng Zhao [1,*], Youcheng Zheng [2], Qiang Liu [2], Yan Zhang [1], Yong Tang [3] and Yuan Xu [1]

[1] Research Institute of Natural Gas Technology, PetroChina Southwest Oil & Gas Field Company, Chengdu 610213, China; y_zhang@petrochina.com.cn (Y.Z.); xu_yuan@petrochina.com.cn (Y.X.)
[2] PetroChina Southwest Oil & Gas Field Company, Chengdu 610015, China; zheng_ych@petrochina.com.cn (Y.Z.); qiang_liu@petrochina.com.cn (Q.L.)
[3] Development Department, PetroChina Southwest Oil & Gas Field Company, Chengdu 610066, China; tangy1987@petrochina.com.cn
* Correspondence: zhaozhiheng@petrochina.com.cn

Abstract: Carbonate formation is the key reservoir in Sichuan Basin for natural gas development. Compared with the early stage of development, the burial depth of targeted formation becomes deeper, and the formation temperature gets higher. So, the characteristics of acidizing effectiveness in high-temperature carbonate formations make this evaluation slightly difficult. Currently, it is common that a single parameter is considered to study acidizing effectiveness by simulation and experiment methods. In this paper, for a more accurate investigation of acidizing effectiveness, multiple parameters, including permeability change rate, fracture conductivity, and surface roughness, were introduced by a series of experiments. It is revealed that the permeability change rate is more than 57% when using gelled acid. As the amount of diverting agent increases in diverting acid, the viscosity of the acid grows to its peak with the reaction, making it easier to block the high permeability core temporarily and divert to acidify the low permeability core, where the permeability change rate of the low permeability core goes from 51.6% to 64.2%, which shows well acidizing effectiveness. In addition, the short-term and long-term conductivity of the samples from the three different formations are more than 200 mD·m under high closure stress. The conductivity of Maokou Formation is the largest due to its high content of carbonate minerals and high dissolution rate. And the results of long-term conductivity are consistent with those of surface roughness, making the evaluation results more reliable for acidizing effectiveness. It is worth noting that temperature is a factor that cannot be ignored in the evaluation of acidizing effectiveness because it has a great influence on the performance of the acid system, such as viscosity and the reaction-reduced rate, leading to an acidizing effectiveness affect. So, the temperature resistance of an acid system is important as well.

Keywords: acidizing effectiveness; high-temperature carbonate formation; permeability; fracture conductivity; surface roughness

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1. Introduction

Carbonate formation, as one of the important conventional reservoirs, is receiving a lot of attention currently. The stimulation of carbonate formation mainly employs acid fracturing, which injects acid into the reservoir to chemically dissolve certain components of rock and block materials in order to communicate pores and form fractures in the formation [1]. In Sichuan Basin, China, carbonate formation is regarded as a promising resource that is required to improve efficiently. At present, as the target carbonate well gets deeper, the temperature of the formation becomes higher. Therefore, how to improve the acidizing effectiveness and increase production are essential problems to be solved in deep carbonate wells.

Recently, many scholars have studied acidizing effectiveness in oil and gas reservoirs. Penny et al. used a horizontal wellbore simulator to study the effect of various additives on matrix acidizing effectiveness in carbonate reservoirs by estimating production [2]. Norlee et al. investigated the effectiveness of emulsified acid on sandstone formation under high-temperature conditions, and emulsified acid could form large and conductive channels within the rock [3]. Zhou et al. revealed that when gelled acid fracturing was applied in carbonate rocks with a low elastic modulus, fracture conductivity cannot be maintained, but fracture conductivity at high displacement is stronger than that at low displacement [4]. Inductively coupled plasma was utilized to characterize liquid flowback samples to evaluate carbonate acidizing by Aldakkan et al., and gelled, emulsified, and straight hydrochloric acids were used to demonstrate the method [5]. Wang et al. studied the influence of different acids on the conductivity of corrosion fracture and indicated that the combination of gelled acid and self-diverting acid gained the maximum fracture conductivity at room temperature [6]. Panjalizadeh et al. adopted the modified inverse injectivity method, which is fully discussed by Safari et al. [7], to evaluate the acidizing matrix in long heterogeneous carbonate reservoirs [8]. Kalabayev et al. conducted research on reservoir rock reactions with various acid and fluid systems to analyze and improve the effectiveness of acid treatments by laboratory testing and modeling, and sensitivity analyses were also considered to evaluate acidizing effectiveness [9]. The influence of acid type, acid amount, and injection mode on fracture conductivity was analyzed by Yang et al. at room temperature, and it was indicated that compared with the one-stage alternating injection of a single acid, the combination of autogenic acid and gelling acid has a stronger dissolution effect, and the conduction capacity is greater [10].

Obviously, through the above research, it is common for simulation and experiment methods to be adopted, and just one parameter is introduced to evaluate acidizing effectiveness. And the long-term flow capacity of the fracture is rarely considered. In addition, the experiments conducted are mainly at room temperature or low temperature. But the target carbonate formation temperature gets to 140–160 °C now, and the temperature conditions cannot meet the research needs. Therefore, in this paper, experiments of permeability change and conductivity are conducted at the formation temperature by injecting different kinds of acid systems, and multiple parameters, characterizing the short-term and long-term flow capacity of fractures, are employed to estimate acidizing effectiveness comprehensively.

2. Evaluation of Acidizing Effectiveness

2.1. Experiment Preparation

Natural gas needs many passages to flow to the well, so the flow capacity of fractures is an essential factor for acidizing effectiveness. In order to fully characterize the flow capacity of fractures, three parameters, permeability change rate, fracture conductivity, and surface roughness, are introduced by experiments. Gelled acid and diverting acid, which are commonly used for acidification in high-temperature carbonate wells, are adopted for experiments. Gelled acid mainly consists of hydrochloric acid, high-effective thickener, corrosion inhibitor, and iron stabilizer. And diverting acid mainly includes hydrochloric acid, diverting agent, corrosion inhibitor, iron stabilizer, and a high-molecular polymer, which is used for carbonate wells in Sichuan Basin.

For permeability change experiments, in order to maintain a single variate, marble cylinders with a diameter of 25 mm and a height of 50 mm are prepared to cut an artificial transverse fracture in the middle of it on the basis of the evaluation criteria (Figure 1). And high-temperature core flow equipment is employed to test the permeability change in marble cylinder before and after injecting gelled acid and diverting acid at the same flow rate. The permeability change rate can be calculated by the comparison of permeability before and after injection acid. The temperature and pressure range of high-temperature core flow equipment are 0~180 °C and 0~60 MPa, which could meet the needs of the experimental requirement.

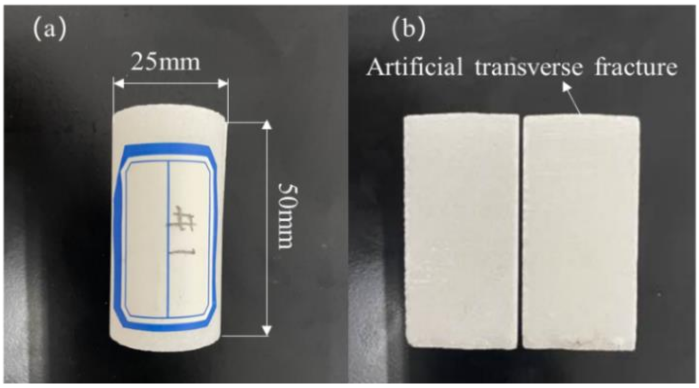


Figure 1. (**a**) Marble cylinder; (**b**) traverse surface of sample.

Another two parameters, fracture conductivity and surface roughness, are mainly obtained by conductivity experiments. The samples are carbonate outcrops from Dengying Formation, Xixia Formation, and Maokou Formation, which are processed into cuboids with a length of 150 mm, a width of 50 mm, and a height of 25 mm according to the evaluation criteria (Figure 2). Acid-etched fracture conductivity equipment is introduced to test the short-term and long-term conductivity by injecting gelled acid and diverting acid, and then a three-dimensional laser scanner is used to obtain the acid-etched surface after the conductivity experiments. The surface roughness is evaluated by the ratio of the surface area before and after the injection of acid. The temperature resistance of the acid-etched fracture conductivity equipment is 180 °C, and its pressure could get to 80 MPa.

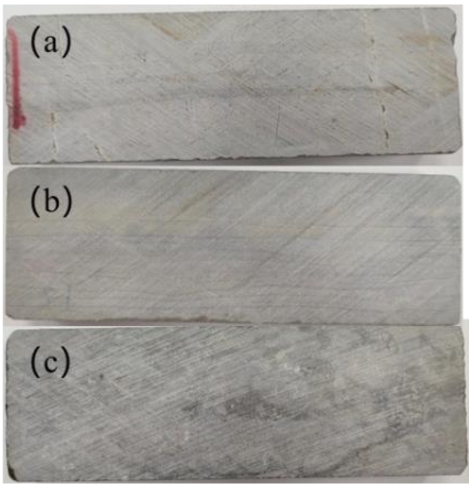


Figure 2. Samples: (**a**) Dengying Formation; (**b**) Xixia Formation; (**c**) Maokou Formation.

2.2. Evaluation of Permeability Change

Permeability is an important parameter for reservoirs, determining the seepage of natural gas to the well. Therefore, one of the indexes of acidizing effectiveness is to characterize the change in permeability before and after the injection of acid. In this part, permeability change experiments were conducted at 160 °C, consistent with the formation temperature. Two kinds of acid systems and different amounts of additives were used to study the permeability change in marble cylinders. During the experiments, the total volume of acid and the injection rate remain the same. The experimental conditions and data are shown in Tables 1 and 2.

Table 1. Experimental conditions and results of gelled acid.

Acid System	Amount of Thickener	Initial Permeability (mD)	Permeability after Acidizing (mD)	Permeability Change Rate (%)
Gelled acid	0.4	6.231	10.362	66.3
	0.6	9.502	14.988	57.7
	0.8	7.974	12.769	60.1

Table 2. Experimental conditions and results of diverting acid.

Acid System	Amount of Diverting Agent	Initial Permeability (mD)	Permeability after Acidizing (mD)	permeability Change Rate (%)
Diverting acid	6	0.182	0.276	51.6
		7.150	Breakthrough	/
	8	0.191	0.304	59.2
		7.228	Breakthrough	/
	10	0.173	0.284	64.2
		6.884	Breakthrough	/

According to the results of the single core permeability test of gelled acid in Table 1, when the amount of thickener is 0.4~0.8%, this basically matches with the amount in the field in different conditions, and the permeability change rate of the marble cylinder is more than 57%, and its maximum could be 66.3%, which means that the permeability of the cores is greatly improved to provide better seepage passages. The blocking ability and diverting ability of diverting acid are mainly investigated at high temperatures, so double core permeability tests are conducted. Two cores with different initial permeabilities are selected, as shown in Table 2. The high permeability core is acidified first and is blocked temporarily due to the increase in the diverting acid's viscosity with the progress of the reaction; then, the diverting acid turns to the low permeability core. As the amount of diverting agent increases, the diverting acid's viscosity gets higher, and the permeability change rate of the low permeability core goes from 51.6% to 64.2%, which shows that is has a better acidizing effectiveness.

2.3. Evaluation of Conductivity Experiment

The conductivity of the acid-etched fracture is closely related to rock strength, formation characteristics, and acid properties. In this part, different formation rocks and acid systems are mainly considered to study their acidizing effectiveness. Through conductivity experiments, two parameters, fracture conductivity and surface roughness, can be obtained. First of all, samples from three formations, Dengying Formation, Xixia Formation, and Maokou Formation, were used to test their short-term fracture conductivity under closure stress with 30~60 MPa at a temperature of 160 °C. During the experiments, the total volume of acid and the flow rate remained the same. Then, a three-dimensional scanner was introduced to scan the sample's surface after the conductivity experiment, and then the fracture roughness was calculated. The experimental conditions are shown in Table 3.

Table 3. Experimental conditions of conductivity test.

Samples	Temperature (°C)	Flow Rate (mL/min)	Total Volume (mL)	Closure Stress (MPa)
Dengying Formation	160	50	1000	30~60
Xixia Formation				
Maokou Formation				

The short-term conductivity of the samples from the three different formations was obtained by gelled acid and is compared in Figure 3. It is implied that as the closure stress goes from 30 MPa to 60 MPa, the short-term conductivity declines, but their decrease degree varies. For the sample from Xixia Formation, its tendency to decrease gets smaller with the growth of closure stress. For samples from Dengying Formation and MaoKou Formation, the tendency to decrease becomes greater when the closure stress spans from 30 MPa to 60 MPa. And for samples from Dengying and Xixia Formations, their decrease rate of short-term conductivity is more than 60%, which means that closure stress has a great effect on their short-term conductivity. In addition, it is clear that the short-term conductivity of the sample from Xixia Formation is smaller than that of the other two samples, but the minimum is also larger than 200 mD·m.

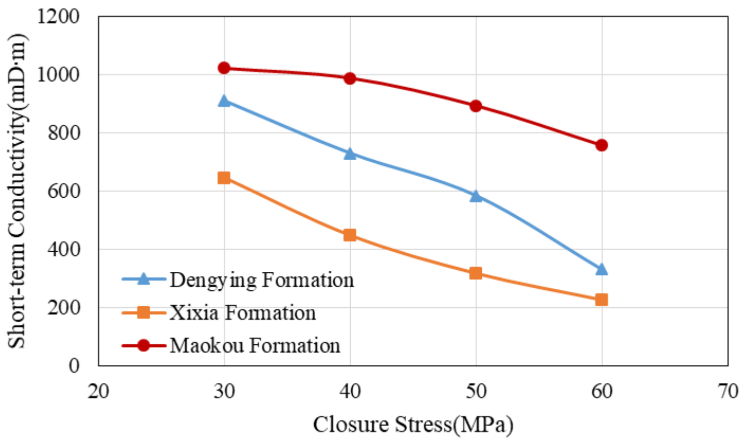


Figure 3. Short-term conductivity of samples under different closure stress used by gelled acid.

Obviously, the results of diverting acid in Figure 4 are basically consistent with those of gelled acid. When the closure stress spans from 30 MPa to 60 MPa, the decrease rates of the short-term conductivity from Dengying Formation and Xixia Formation samples are larger, with mostly 50~60% compared with that of Moukou Formation. But when the closure stress spans from 50 MPa to 60 MPa, the decrease rate of the short-term conductivity from Dengying Formation suddenly becomes large. Also, the short-term conductivity of the sample from Xixia Formation is smallest, and when the closure stress rises to 60 MPa, the short-term conductivity is 213 mD·m.

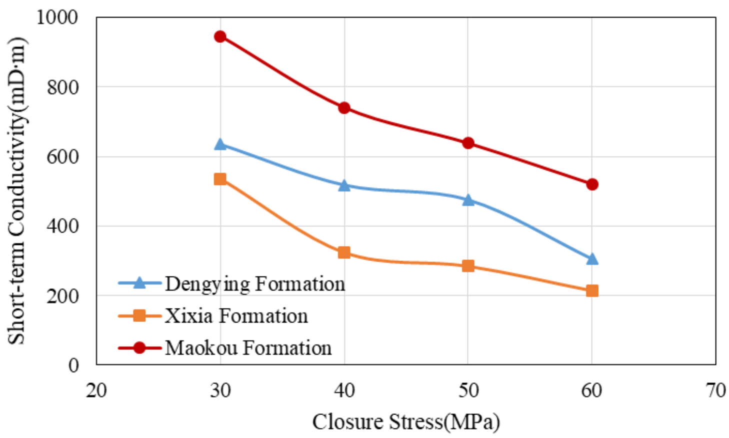


Figure 4. Short-term conductivity of samples under different closure stress used by diverting acid.

Moreover, except for the short-term conductivity that has been discussed, the long-term conductivity is equally important for the acidizing effectiveness of gas wells, which contributes to their production [11]. The long-term conductivity of acidified fractures was studied at 60 MPa closure stress and 160 °C temperature for 1 hour. From Figures 5 and 6, it is revealed that for gelled acid and diverting acid, the long-term conductivity of the Maokou Formation sample is the largest. Also, the long-term conductivity of the three formation samples is more than 200 mD·m under high closure stress and high temperature. Moreover, as the experiment goes on, long-term conductivity has a slow descent for the first 10 minutes, then it barely drops and tends to remain constant, and the conductivity maintain rate could get to 95%, which means that many effective fractures are formed by injecting gelled acid and diverting acid.

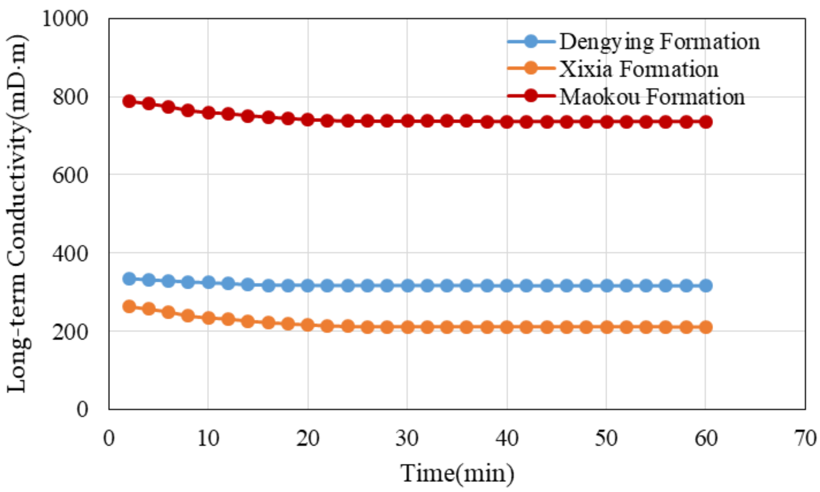


Figure 5. Long-term conductivity of samples by gelled acid.

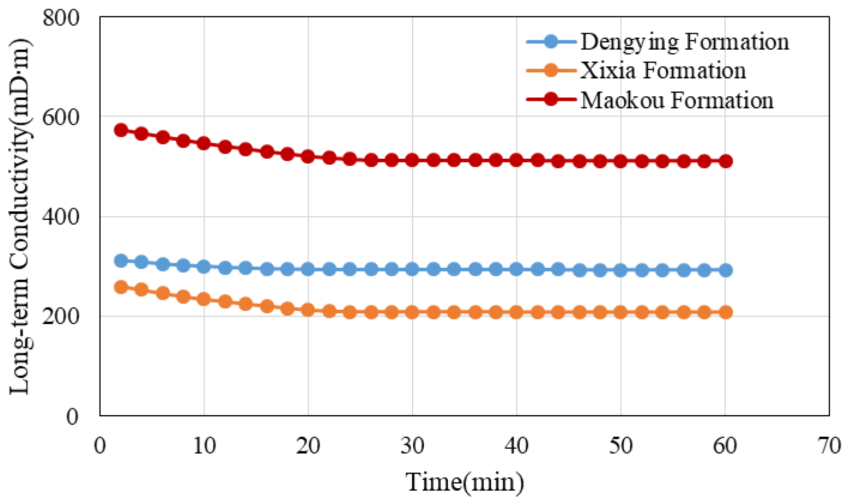


Figure 6. Long-term conductivity of samples by diverting acid.

In addition, the surface roughness of the sample was investigated after the short-term conductivity experiment. A three-dimensional scanner was used to scan the surfaces of the samples. After scanning, the sample surface could be imaged by 3D reconstruction software, and the surface area could be obtained. The surface roughness is calculated by Formula (1) [12,13].

$$D = S_f/S \quad (1)$$

D—Surface roughness, dimensionless;
S—Initial surface area, cm^2;
S_f—Surface area after acidizing, cm^2.

Table 4 shows the acidified surface and surface roughness of gelled acid at 60 MPa, and different colors mean different rough surfaces. It is obtained that the surfaces of the three formation samples after acidizing exhibit varying degrees of roughness, and the surface roughness of the sample from Maokou Formation is the largest of the three with 1.31, resulting in forming better flow passages. And the sample from Xixia Formation is the smallest with 1.08. For the diverting acid in Table 5, the roughness is also different at 60 MPa. Just like the results of gelling acid, the surface roughness of the sample from Maokou Formation is 1.27, which is larger than that of the Dengying Formation and Xixia Formation samples, contributing to the higher conductivity.

Table 4. Surface roughness and acidified surface of gelled acid.

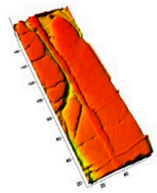
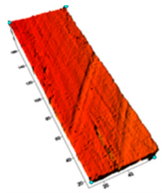
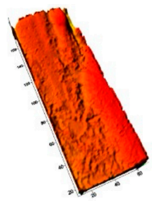
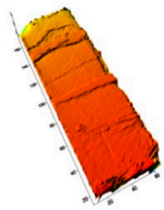
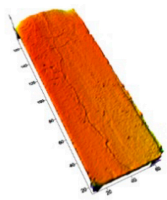
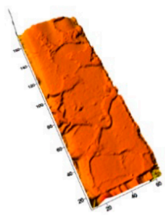
Samples	S (cm^2)	S_f (cm^2)	D	Acidified Surface
Dengying Formation	75.40	91.55	1.21	
Xixia Formation	75.86	82.06	1.08	
Maokou Formation	75.09	98.36	1.31	

Table 5. Surface roughness and acidified surface of diverting acid.

Samples	S (cm^2)	S_f (cm^2)	D	Acidified Surface
Dengying Formation	75.41	90.04	1.19	
Xixia Formation	74.89	79.62	1.06	
Maokou Formation	75.13	95.62	1.27	

3. Discussion

3.1. Multi-Parameter Evaluation

In the evaluation of acidizing effectiveness, the permeability change and conductivity experiments were conducted at a high formation temperature, and the permeability change rate, fracture conductivity, and surface roughness of gelled acid and diverting acid were obtained. Permeability is one of the key parameters used to characterize the flow of oil and gas in pores, so it is proved to be necessary to employ an increase in the degree of permeability to evaluate the acidizing effectiveness [14,15]. Gelled acid and diverting acid are often used in the field for carbonate well acidification, and their permeability change rates reach more than 50%. Diverting acid is mainly adopted to stimulate the carbonate formation with strong heterogeneity. In the double core experiments above, the two marble cores exhibit tremendously various permeability, with an almost 39-times difference. As the amount of diverting agent increases, the peak viscosity of the acid grows with the process of the reaction between the acid and carbonate, making it easier to block the high permeability core temporarily and then divert it to acidify the low permeability core [16,17], which means that the diverting acid system has well temperature resistance and makes the permeability change rate larger.

The Dengying Formation, Xixia Formation, and Maokou Formation are key reservoirs of carbonate development in Sichuan Basin [18], and their short-term conductivity has been tested above. The results show that it does not matter what formation the core is; the short-term conductivity is more than 200 mD·m under high closure stress and high temperature, meeting the requirement of the carbonate formation acidizing stimulation. Obviously, the short-term conductivity of Maokou Formation is the largest among that of the three; this is because of the high content of the carbonate minerals and the high dissolution rate, with more than 90%.

The long periodic production of gas well depends on many factors, and the long-term conductivity of acidified fracture is one of the vital parameters [19,20]. Undoubtedly, as shown in Figure 7, for gelled acid and diverting acid, the results of long-term conductivity are consistent with these of surface roughness, and the increase trends are also similar. As the surface roughness increases, making the acidified fracture easier to be supported and harder to close at high closure stress, long-term conductivity tends to grow. Additionally, the long-term conductivity of Maokou Formation is highest among that of the three. So, Maokou Formation is becoming a key development formation in the Sichuan Basin, and some carbonate wells have achieved high test production with 100×10^4 m^3/d.

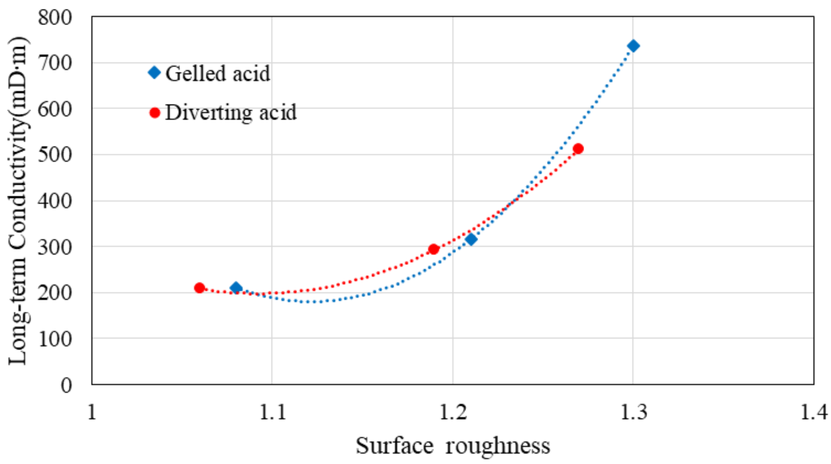


Figure 7. Relationship curve between surface roughness and long-term conductivity.

3.2. High-Temperature Resistance Evaluation

Temperature has a great influence on the performance of the acid system, and high-temperature resistance is a major challenge for acid systems, so temperature is a key factor for acidizing effectiveness in carbonate wells. For low-temperature carbonate formation, the properties of the acid system can meet the requirements of the stimulation. However, when the temperature gets to more than 150 °C, the properties of the conventional acid system, including its viscosity, reaction-reduced rate, and corrosion resistance [21], will deteriorate, which makes the acidizing effectiveness worse to some extent. Therefore, high requirements are put forward for high-temperature acid technology. In the experiments, the key additives in the gelled acid and diverting acid adopted have been optimized and well designed for high-temperature carbonate formation, and the temperature resistance of gelled acid and diverting acid could reach 180 °C, and their viscosity, reaction-reduced rate, and corrosion resistance meet the evaluation criteria at high temperatures. So, they are suitable for almost all carbonate formation stimulations in Sichuan Basin [15,22,23].

For the evaluation of acidizing effectiveness at high temperatures, the viscosity and reaction-reduced rate of acid are two essential parameters. In permeability change experiments, if the temperature resistance of diverting acid is not good enough to obtain high viscosity, it will be not able to block the high permeability core and divert to acidify the low permeability core. In conductivity experiments, the fractures with conductivity are formed mainly by acid etching. High viscosity is required for acid to slow the mass transfer rate of hydrogen ions to reduce the reaction rate [24], making acid flow forward and form long fractures instead of just forming short fractures at the injection end, which cannot achieve good acidizing effectiveness.

4. Conclusions

In order to characterize acidizing effectiveness better in high-temperature carbonate formations, multiple parameters were introduced by a series of evaluation experiments. The conclusions are shown below:

(1) Based on the permeability change evaluation, the permeability change rates of marble cylinders are more than 57%, and the maximum could get to 66.3% when using gelled acid. As the amount of diverting agent increases in diverting acid, the permeability change rate of the low permeability core goes from 51.6% to 64.2%, which has well acidizing effectiveness.

(2) According to the conductivity experiment evaluation, it is revealed that the short-term and long-term conductivity of samples from three different formations are more than 200mD·m under high closure stress and high temperatures. And the results of long-term conductivity are consistent with these of surface roughness, making the evaluation results more reliable for acidizing effectiveness.

(3) In the evaluation of acidizing effectiveness, temperature is an essential condition. Temperature has a great influence on the performance of an acid system, such as viscosity and the reaction-reduced rate of an acid system, leading to having an effect on acidizing effectiveness.

(4) One single parameter cannot evaluate acidizing effectiveness well. A multi-parameter approach, including permeability change rare, conductivity, and surface roughness, is more comprehensive and accurate for investigating acidizing effectiveness in high-temperature carbonate formations.

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References

1. Parandeh, M.; Dehkohneh, H.Z.; Soulgani, B.S. Experimental investigation of the acidizing effects on the mechanical properties of carbonated rocks. *Geoenergy Sci. Eng.* **2023**, *222*, 211447. [CrossRef]
2. Penny, G.; Biswas, D.; Germack, D.; Shedd, D.; El Din, N. The Effect of Various Additives on Matrix Acidizing Effectiveness in Carbonate Reservoirs. In Proceedings of the First Eage Workshop on Well Injectivity & Productivity in Carbonates, Doha, Qatar, 30 March–1 April 2015.
3. Norlee, A.; Shi, T.; Mahmud, H.K.B. Investigating the Effectiveness of Emulsified Acid on Sandstone Formation under High Temperature Conditions. In *IOP Conference Series: Materials Science and Engineering, Proceedings of the Curtin University Technology, Science and Engineering International Conference, Sarawak, Malaysia, 26–28 November 2018*; IOP Publishing: Bristol, UK, 2019.
4. Zhou, J.; Zou, H.; Zhu, D.; Xiong, W. Experimental study on the fracture conductivity in the carbonate reservoirs with low elastic modulus. *Oil Drill. Prod. Technol.* **2020**, *6*, 752–756.
5. Aldakkan, B.; Moajil, A.M.A.; Alnoaimi, K. Carbonate Acidizing and Flowback Analysis—A Review and an Evaluation Method. In Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Bangkok, Thailand, 28 August 2018; p. SPE-191017-MS.
6. Wang, M.; Wu, Y.; Sun, H.; Chen, P.; Jia, X. Influence of Acid on the Conductivity of Acid Corrosion Fracture. *Spec. Oil Gas Reserv.* **2019**, *5*, 153–158.
7. Safari, A.; Panjalizadeh, H.; Pournik, M.; Jafari, H. A Comprehensive Method for Diverter-Performance Evaluation during Stimulation of Long-Interval Heterogeneous Reservoirs: A Case Study. *SPE Prod. Oper.* **2020**, *36*, 22–33. [CrossRef]
8. Panjalizadeh, H.; Safari, A.R.; Kamani, M. An Efficient Interpretation Method for Matrix Acidizing Evaluation and Optimization in Long Heterogeneous Carbonate Reservoirs. *SPE Prod. Oper.* **2021**, *36*, 780–794. [CrossRef]
9. Kalabayev, R.; Kruglov, R. Increasing the Efficiency of Carbonate Acidizing: Kazakhstan Case Studies. In Proceedings of the SPE Annual Technical Conference and Exhibition, Virtual, 5–7 October 2020.
10. Yang, Z.; Zhong, P.; Wang, H.; Mao, Y.u.; Yi, L.; Li, X. Experimental Study on the Conductivity of Acid Etching Cracks in Penglai Gas Are. *Sci. Technol. Eng.* **2023**, *23*, 1671–1815.
11. Liu, P.; Hu, H.; Chen, X.; Du, J.; Liu, J.; Liu, F.; Chen, W.; Jia, Y. The influencing parameters and improve methods of acid-etched fracture conductivity: A review. *Geoenergy Sci. Eng.* **2024**, *238*, 212844. [CrossRef]
12. Zhao, Z.; Li, X.; He, J.; Mao, T.; Zheng, B.; Li, G. A laboratory investigation of fracture propagation induced by supercritical carbon dioxide fracturing in continental shale with interbeds. *J. Pet. Sci. Eng.* **2018**, *166*, 739–746. [CrossRef]
13. Sistrunk, C.; Brashear, A.T.; Hill, D.; Zhu, D.; Tajima, T. The Effect of Fracture Surface Roughness on Propped Fracture Conductivity Using 3D-Printed Fracture Surfaces. In Proceedings of the SPE Western Regional Meeting, Anchorage, AL, USA, 22–25 May 2023.
14. Bennion, D.B.; Bachu, S. Drainage and Imbibition CO2/Brine Relative Permeability Curves at Reservoir Conditions for High-Permeability Carbonate Rocks. In Proceedings of the SPE Annual Technical Conference and Exhibition, Florence, Italy, 20–22 September 2010; p. SPE-134028-MS.
15. Zhao, Z.; Ma, Y.; Zhang, Y.; Lan, K.; Zhang, X. Evaluation and Application of Efficient Gelled Acid for Carbonate Formation Fracturing. *ACS Omega* **2023**, *8*, 26201–26205. [CrossRef] [PubMed]
16. Deidre, T.; Kumar, P.; Diankui, F. Viscoelastic Surfactant Based Self-Diverting Acid for Enhanced Stimulation in Carbonate Reservoirs. In Proceedings of the SPE European Formation Damage Conference Society of Petroleum Engineers, The Hague, The Netherlands, 13–14 May 2003.
17. Li, S.; Zhang, H.; Wang, M.; Zhang, X.; Zhou, C.; Hu, Q. Experimental evaluation and process optimization of temporary plugging to acid-frac in fractured carbonate reservoirs. *Chem. Eng. Oil Gas* **2021**, *50*, 90–95.
18. Guo, J.; Gou, B.; Lu, D.; Liu, Z.; Xiao, B.; Xu, K.; Ren, J. Advance and Prospect of Acid Fracturing in Deep Carbonate Reservoirs. *Drill. Prod. Technol.* **2024**, *47*, 121–129.
19. Gelius, L.; Wang, Z. Modelling production caused changes in conductivity for a siliciclastic reservoir: A differential effective medium approach. *Geophys. Prospect.* **2008**, *56*, 1365–2478. [CrossRef]
20. Karimi, S.; Bareither, C.A.; Scalia, J. Influence of oil and gas exploration and production waste on municipal solid waste hydraulic conductivity. *Waste Manag.* **2023**, *166*, 211–221. [CrossRef] [PubMed]
21. Khormali, A.; Ahmadi, S. Experimental and modeling analysis on the performance of 2-mercaptobenzimidazole corrosion inhibitor in hydrochloric acid solution during acidizing in the petroleum industry. *J. Pet. Explor. Prod. Technol.* **2023**, *13*, 2217–2235. [CrossRef]
22. Zhao, Z.; Sun, C.; Liu, Y. High-Temperature-Resistant Diverting Acid for Carbonate Formation Fracturing in Sichuan Basin: A Property Evaluation and Field Study. *Geofluids* **2022**, *2022*, 1832993. [CrossRef]

23. Sun, C.; Liu, Y.; Yang, Z.; He, C.; Mei, Z. Research of steering acid type selection and its application in Gao-Mo block Dengying formation of Sichuan Basin. *Chem. Eng. Oil Gas* **2019**, *48*, 70–74.
24. Welton, T.D.; Domelen, M.S.V. High-Viscosity-Yield Acid Systems for High-Temperature Stimulation. *SPE Prod. Facil.* **2008**, *23*, 177–183. [CrossRef]