

## Research Article

# High-Temperature-Resistant Diverting Acid for Carbonate Formation Fracturing in Sichuan Basin: A Property Evaluation and Field Study

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The targeted carbonate formation in Gao-Mo Block located in the middle of Sichuan Basin becomes deeper with the progress of development, and it mainly exhibits high temperature and strong heterogeneity. Higher requirements for temperature resistance performance and acidizing effect of diverting acid are put forward. In this work, the high-temperature-resistant diverting acid (HTRDA) was employed to evaluate the compatibility, temperature resistance, friction reduction, and acidizing effectiveness based on formation characteristics, and it was applied to demonstrate its reliability and adaptability in field. The following study results are obtained. The HTRDA has good compatibility and its peak viscosity could reach 31 mPa·s at the temperature of 170°C. Compared with the friction of water, the friction reduction rate of HTRDA can reach 67.8%. And the permeability change of core with low permeability could be increased by 53.5-61% after acidification. Furthermore, during the acid fracturing of Well M, the maximum diverting pressure of HTRDA gets to 10 MPa and the friction reduction rate is about 66.5% that is consistent with the experimental data. The test production of Well M is  $35.64 \times 10^4 \text{ m}^3/\text{d}$  and the acid fracturing obtain a great result.

## 1. Introduction

Sichuan Basin is rich in natural gas resources, and the carbonate formation in Gao-Mo Block as one of significant development targets exhibits huge potential. Previously, diverting acid is a main mean to stimulate carbonate formation and has achieved great results in Gao-Mo Block, in which the test production of many wells reaches to  $30\text{-}50 \times 10^4 \text{ m}^3/\text{d}$  [1]. With the progress of exploration, the burial depth and temperature of targeted carbonate formation become deeper and higher, and the heterogeneity of formation is strong in Gao-Mo Block. Therefore, higher requirements for temperature resistance performance and acidizing effect of diverting acid are put forward.

Diverting acid for carbonate formation fracturing has been studied by many scholars so far. Li et al. introduced the diverting acid with peak viscosity 100 mPa·s at temperature 90°C to the Mishrif reservoir in Iraq. It has excellent

performance in corrosion resistance and iron stability, and the permeability of cores could be increased by 59.2% after acidification [2]. Taylor et al. synthesized the diverting agent and developed the diverting acid system based on formation characteristics in Kuwait area. It has the limitation of the thermal stability at about 130°C, and the peak viscosity is about 20 mPa·s [3]. The diverting acid was obtained by erucamide hydroxyl sulfonate amphoteric surfactant viscoelastic diverting agent, corrosion inhibitor with high temperature resistance, and cationic oligomer temperature inhibitor by Ma. Its thermal stability is at 150-160°C, and the peak viscosity is about 40 mPa·s, which exhibits good self-diverting performance [4]. Zhang et al. synthesized a viscoelastic surfactant by erucamide propyl dimethyl tertiary amine and epoxy chloropropane and formed the diverting acid system that has peak viscosity about 50 mPa·s at 120°C. It can increase the permeability of carbonate cores by 2.35 times and has been widely applied in field [5, 6].

TABLE 1: Main experiment materials and equipment.

Experiment materials	1	Diverting agent	5	Iron stabilizer
	2	Corrosion inhibitor	6	Mud from well
	3	High-molecular polymer	7	Carbonate cuttings
	4	Hydrochloric acid	8	Carbonate cores
Experiment equipment	1	Six speed rotary viscometer	3	High temperature and pressure acidizing displacement instrument
	2	GLM-200 acidizing friction instrument	4	MicroXCT-400 scanner

Alleman et al. developed the diverting acid system that its temperature resistance is up to 170°C and the peak viscosity is about 20 mPa·s. This diverting acid system has been applied more than 15 wells in the Gulf of Mexico [7]. Schlumberger developed and optimized the diverting acid that is suitable for reservoirs with the highest temperature of 160°C. More than 70 wells have been stimulated to verify its property and effect for acidizing fracturing [8–10].

The researches above indicated that the temperature resistance for diverting acid is 165°C. And the peak viscosity is not large enough for higher temperature reservoir to realize effective stimulation. At present, the burial depth of carbonate formation gets to 7500 m, and the temperature reaches 170°C in Sichuan Basin. Besides, the carbonate formation exhibits strong heterogeneity that the porosity is 2–8% and the permeability difference can reach 53 times, so it is difficult to achieve acid uniform distribution. Therefore, in order to improve acid fracturing effectiveness, the compatibility, temperature resistance, friction reduction, and acidizing effectiveness of high-temperature-resistant diverting acid (HTRDA) were evaluated based on formation characteristics. And the HTRDA was applied to demonstrate its reliability and adaptability in field.

## 2. Property Evaluation of HTRDA

**2.1. Experiment Material and Equipment.** The diverting agent used in the experiment is mainly synthesized through the erucic acid group, amido propyl group, and hydroxyl sulfonate group as the main functional group in the laboratory, and the effective content is 40–60%. 20% hydrochloric acid and 3% corrosion inhibitor are used, and 1% iron stabilizer is added based on formation characteristics in Sichuan Basin [11]. To reduce friction, 0.1% high-molecular polymer is introduced. The specific experiment materials and equipment are listed in Table 1.

### 2.2. Experiment Results

**2.2.1. Compatibility Evaluation.** The compatibility is one of the basic properties for diverting acid evaluation. In this section, hydrochloric acid, additives, and mud are used to mix with diverting agent, respectively, leaving mixed solutions for 24 h at the temperature of 170°C to discuss the compatibility. The experiment results are shown in Table 2.

According to the above experimental results, the diverting agent has good compatibility with hydrochloric acid and additives and there is no precipitation and stratification.

When HTRDA was mixed with mud, they could react with each other due to the existence of drilling cuttings in mud, which could promote the removal of mud damage.

**2.2.2. Temperature Resistance Evaluation.** As the temperature of carbonate reservoir becomes higher in Sichuan Basin, the temperature resistance of diverting acid is required to be improved. The HTRDA is reacted with different amounts of calcium carbonate, and the maximum viscosity value is obtained. Then, the peak viscosity can be tested at a shear rate of 170S<sup>-1</sup> at a temperature of 30–175°C. Figure 1 shows the peak viscosity of the HTRDA at different temperatures. The peak viscosity of conventional diverting acid was conducted at the temperature of 170°C at the same way.

It can be seen from the figure that when the temperature reaches 60°C, the peak viscosity of the HTRDA decreases gradually with the increase of temperature. And the peak viscosity can still reach 31 mPa·s at the temperature of 170°C, which is higher than that of conventional diverting acid with about 10 mPa·s. So the HTRDA exhibits a good temperature resistance.

**2.2.3. Friction Reduction Evaluation.** Wellbore friction is a problem that cannot be ignored in acidizing fracturing, especially in that of deep wells. The GLM-200 acidizing friction instrument was employed to compare and analyze the friction reduction of the HTRDA, conventional diverting acid, and water at room temperature. And the inner diameter of the pipeline is 8 mm. The friction of the three kinds of liquids is shown in Figure 2.

It is obtain in the figure that with the growth of linear velocity, the friction of the three liquids increases. The friction of HTRDA is just 209 KPa at linear velocity 10 m/s that is lower than that of conventional diverting acid. And compared with the friction of water, the friction reduction rate of HTRDA can reach 67.8%, which meets requirements in field greatly.

**2.2.4. Acidizing Effectiveness Evaluation.** Acidizing effectiveness directly affect well production in carbonate formation stimulation. In this study, two cores with different permeability were selected to simulate reservoirs with different permeability, and two groups of experiments were conducted at the temperature of 170°C with the confining pressure of 20 MPa. The HTRDA acidified the high permeability core first, and with the progress of reaction, the viscosity of HTRDA increased and temporary plug was formed, which made the HTRDA enter the low permeability core. The

TABLE 2: Experiment results of compatibility.


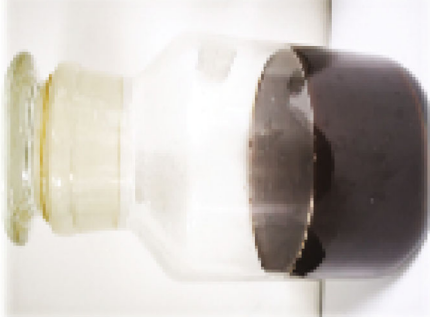

Mixed solution	Compatibility description after 24 h	Experiment picture
6%diverting agent + 20%hydrochloric acid	No precipitation and stratification	
HTRDA (6%diverting agent + 20%hydrochloric acid + 3%corrosion inhibitor + 1%iron stabilizer + 0.1%high – molecular polymer)	No precipitation and stratification	

TABLE 2: Continued.

Mixed solution	Compatibility description after 24h	Experiment picture
HTRDA + mud	Reacting with mud	

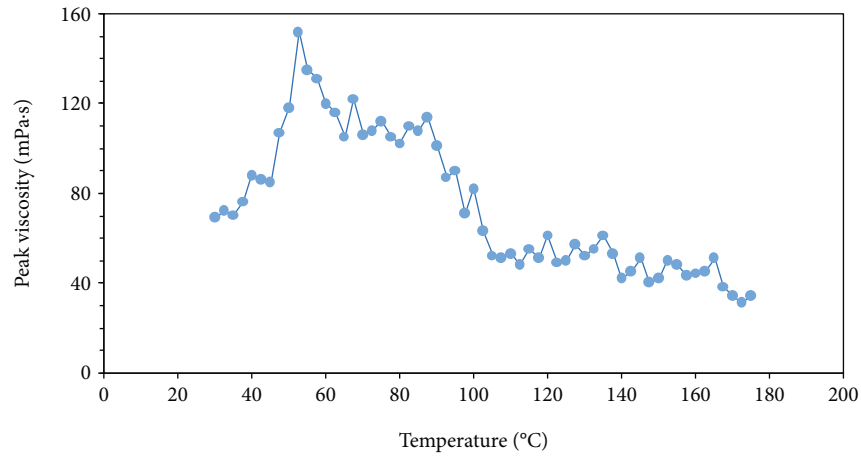


FIGURE 1: Relationship between peak viscosity and temperature.

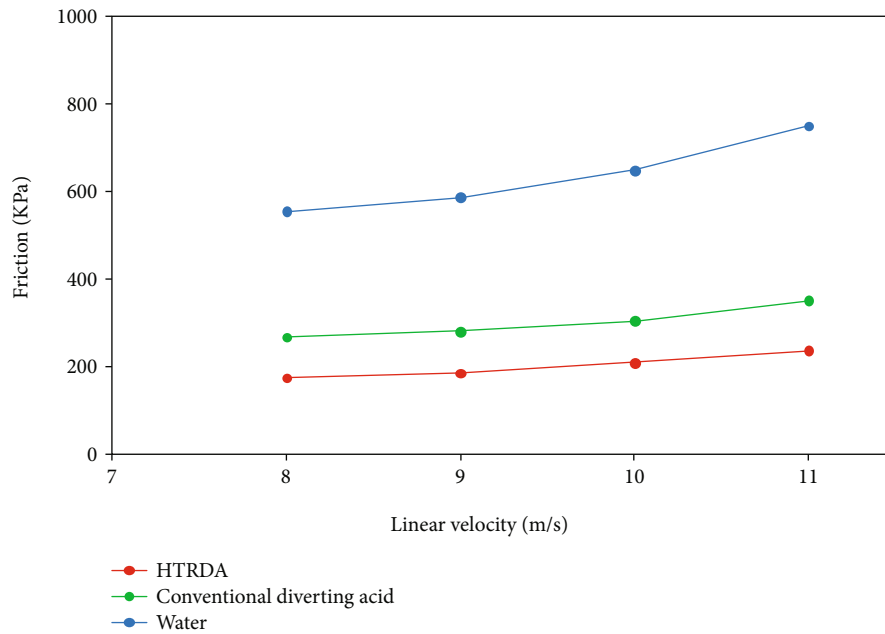


FIGURE 2: Friction of three kinds of liquids.

TABLE 3: Double-core acidification experiment data.

Group no.	Core no.	Initial permeability (mD)	Permeability after acidizing (mD)	Permeability difference (times)	Acidizing effectiveness (%)
Group 1	1	2.8772	Breakthrough	57.1	/
	2	0.0504	0.0811		60.9
Group 2	3	7.9501	Breakthrough	52.2	/
	4	0.1523	0.2337		53.5

experiment data of acidizing effectiveness are shown in Table 3.

According to the results of Group 1 experiment at 170°C, after breakthrough of high permeability core (Figure 3(a)), the permeability of low permeability core increased from 0.1523 mD to 0.2337 mD (Figure 3(b)), and the acidizing effectiveness was increased by 60.9%. In Group 2, the acidiz-

ing effectiveness was improved by 53.5% as well. So the HTRDA has a remarkable self-diverting performance under high temperature.

2.3. Discussion. The compatibility, temperature resistance, friction reduction, and acidizing effectiveness of HTRDA were evaluated in the experiment above. For its

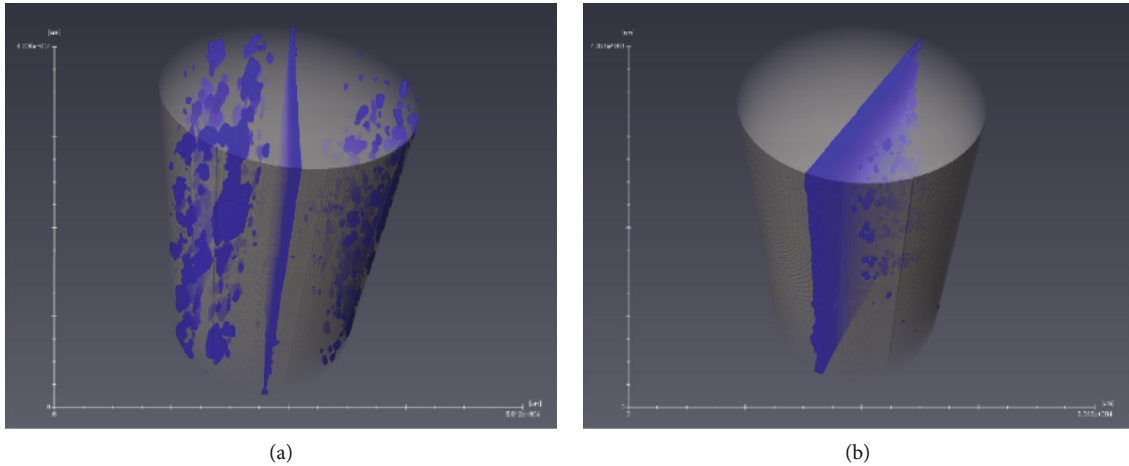


FIGURE 3: CT scan of the core after acidizing in Group 1.

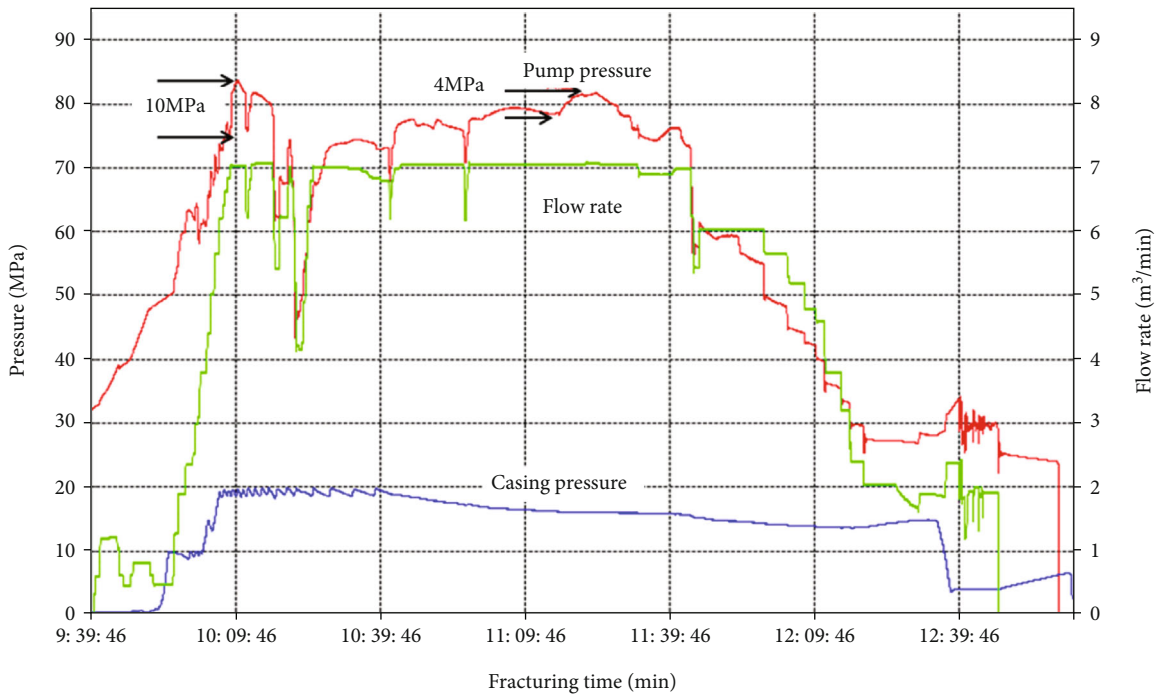


FIGURE 4: Acid fracturing curve of Well M.

compatibility, the precipitation and stratification are not produced and HTRDA can react with cuttings in mud, which means that there is no damage to the formation and it could promote the removal of mud damage in bottom hole. It has been known that the temperature resistance of diverting acid has reached 170°C. But in this work, the peak viscosity of HTRDA can get to 31 mPa·s at the temperature of 170°C, which is higher than that of other diverting acid [12, 13]. In heterogeneous carbonate reservoirs, the diverting acid with higher peak viscosity is easier to block the formation with high permeability and then turns to the formation with low permeability in favor of uniform acid distribution.

For the development of carbonate formation in Sichuan Basin, the length of horizontal well gets to 6500 m or more, so reducing friction exhibits a great importance. Compared

with the friction of water, the friction reduction rate of HTRDA is 67.8% which is much higher than that of conventional diverting acid of just 53%. The high friction reduction rate could decrease fracturing pressure and provide conditions for large flow rate, which is beneficial to acid fracturing efficiently.

At present, the diverting ability and acidizing effectiveness of diverting acid are mainly determined by viscosity [14], and the most commonly used method is to characterize the pressure change in the process of injection by acid and brine in the cores. The large change of pressure indicates that the viscosity of acid increases to form temporary block in the acidizing process, but it cannot represent and quantitative the degree of acidizing effectiveness [15]. So permeability change of cores with different permeability is used

to evaluate the acidizing effectiveness of HTRDA in this work. At the condition of temperature 170°C, the permeability change of core with low permeability could be increased by 53.5-61%, which could provide more passages for gas to flow. So the HTRDA has a great acidizing effectiveness.

### 3. Field Study

Well M is a high temperature horizontal well with vertical deep 5230 m in Gao-Mo Block. The carbonate formation of Well M performs strong heterogeneity that the maximum permeability is 2.223 mD and the minimum is 0.0443 mD, and the permeability difference is 51.7 times. The temperature of bottom hole reaches 165°C. The HTRDA was used for the acid fracturing.

The acid fracturing curve of Well M is shown in Figure 4. It is indicated that when the flow rate is 7.0m<sup>3</sup>/min, the pump pressure rises several times and the maximum diverting pressure is 10 MPa, which means the diverting effectiveness of HTRDA is remarkable. At the later stage of acid fracturing, when the reaction between acid and the carbonate is basically finished, pump pressure reaches 61.85 MPa at a certain flow rate and stop pump pressure is 27.58 MPa. The calculated friction is 34.27 MPa (about 6.55 MPa/1000 m). Compared with water friction, the friction reduction rate of HTRDA is about 66.5%. The test production of Well M is 35.64 × 10<sup>4</sup> m<sup>3</sup>/d that achieves a great result.

### 4. Conclusions

- (1) In order to meet the requirements of acidizing fracturing in carbonate formation with high temperature, the properties of developed high temperature resistant diverting acid (HTRDA) were evaluated. The HTRDA has good compatibility and its peak viscosity could reach 31 mPa·s at the temperature of 170°C. Compared with the friction of water, the friction reduction rate of HTRDA can reach 67.8%. Besides, the permeability change of core with low permeability could be increased by 53.5-61% after acidification. So the HTRDA has a great acidizing effectiveness
- (2) The HTRDA has been applied in Well M. During the acid fracturing, the maximum diverting pressure gets to 10 MPa and the friction reduction rate is about 66.5% that is consistent with the experimental data. The test production of Well M is 35.64 × 10<sup>4</sup> m<sup>3</sup>/d and the acid fracturing used by HTRDA obtains a great result

### Data Availability

The data used to support the findings of this study are included within the supplementary information file.

### Conflicts of Interest

The authors declare no conflict of interest.

### Acknowledgments

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### Supplementary Materials

*Supplementary 1.* Data for relationship between peak viscosity and temperature.

*Supplementary 2.* Data for friction of three kinds of liquids.

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