LABORATORY STUDY ON ACID FRACTURING PERFORMANCE IN HIGH TEMPERATURE CARBONATE RESERVOIRS

by

Xiong ZHANG[a], Xu-Sheng CAO[a], Yao-Yao SUN[b*], Lian LIU[a], Bing ZHAO[a], and Yun-Di GENG[a]

[a] SINOPEC Northwest Oilfield Branch, Urumqi, China
[b] China University of Petroleum-Beijing, Beijing, China

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In this article, we investigate acid fracturing, a promising method to increase the effectiveness of fractures in high temperature carbonate reservoirs. In order to determine the performance of acid fracturing in carbonate reservoirs, we conducted a lab scaled true triaxial acid fracturing experiment on high temperature carbonate rock. The fracture initiation, propagation behavior, and conductivity under the action of acid solution were analyzed. The 3-D micro computed tomography was applied to illuminate the fracture network patterns; coefficient of stress difference, acid etching time, and acid concentration were also analyzed. Results show acidification exhibits the lowest breakdown pressure compared with no-acidification, reduced by 58%.

Keyw ords: *geothermal, high temperature carbonate, acid fracturing, acidification, conductivity*

Introduction

Geothermal energy is an important part of the world's energy plan for the 21th century. It has many benefits over traditional energy sources, including being clean, efficient, and having large reserves [1]. Fault-karst reservoir is a promising geothermal storage space. High temperature carbonate reservoir is the main enrichment form of fault-karst reservoir, which offers tremendous potential for thermal energy [2].

Acid fracturing serves as the primary stimulation method in the development of carbonate reservoirs, which has been increasingly applied in recent years. Acid etching is main cause to increase effective fracture length [3]. The roughness of the fracture surface is helpful to self support between fracture surfaces, as to increase the effectiveness of the fracture [4]. Because of the fractures has low degree of closure, fluid-flow speed and seepage area are maintained. Acidification is a means to blockage relieving of acid fracturing method. In past research, we conducted on fracture propagation in oil and gas reservoirs due to acid fracturing [5]. However, unlike oil and gas reservoir, the acidification of high temperature geothermal reservoir is more complicated. The initiation and propagation of fractures for geothermal carbonate takes the joint action of thermal stress and acid corrosion, and thereby show a significant difference with that in oil and gas reservoir [6]. It is necessary to study initiation and propagation of acid fracturing fractures in high temperature carbonate formation behavior, to better understand the stimulation mechanism of this method in geothermal reservoir [7, 8].

[*] Corresponding author, e-mail: sunyy1009@163.com

Experimental equipment and experimental methods

Experimental material and equipment

In this work, carbonate rock samples with the dimension of 300 mm × 300 mm × 300 mm were used. These samples were collected from natural outcrop carbonate in Shandong Province, and they are characterized by apparent stratification in rock bedding and significant heterogeneity internally. Before the fracturing experiments, the carbonate samples were cut into a cube with a side length of 300 mm, from which a central hole of 16 mm in diameter and 200 mm in depth was drilled to simulate the scaled-down main borehole, as illustrated in fig. 1. A 14 mm diameter metal casing extending 150 mm into the vertical main borehole was cemented using the temperature-resistant epoxy-resin adhesive. with an open-hole section of 50 mm at the bottom.

Figure 1. Experimental material and true triaxial acidizing fracturing equipment

This experiment used a self-made true triaxial-loading system, a liquid injection system, and a data acquisition system to simulate fracturing processes. This simulation system, primarily composed of a confining pressure kettle, a cushion plate, and a hydraulic stability system, can load cubic rock blocks measuring between 100 mm and 400 mm. The primary function of the liquid injection system is to pump dyed water, which acts as the fracturing fluid. The operational end tracks changes in water injection volumes and pressures, simultaneously collecting data. In this experiment, the fracturing sample was injected with dyed water at a steady rate of 30 ml per minute. An acid-resistant intermediate container was adopted for the pressurized injection of acidic fluids.

Experimental procedure and data acquisition

Here, we present the program as follows.

Rock heating:

- Place carbonate sample in a heating furnace and heated to 150 °C.
- Confining pressure loading: move the heated rock in a confining pressure kettle and apply the target triaxial confining pressure.
- Acidification: put 100 ml of 20% hydrochloric acid solution into the wellbore for the acidification reaction.
- Fracturing: once the acidification reaction was complete, pump fracturing fluid with the injection system and monitor the pressure curve.
- The pressure curve was then maintained at a stable level before stopping injection pump.

– Acid etching reaction: connect the intermediate container and inject acid into the wellbore at a constant rate of 30 ml/min for 120 seconds.
– Conductivity test: remove intermediate container and reinject water at a continuous injection rate of 300 ml to record fracturing curve and calculate the conductivity.

Experimental scheme

In this research, we target a separate carbonate sample for fracture analysis. Consider the fracturing procedure, water as the primary fracturing fluid, and maintaining rate of 30 ml per minute. We examined the impact of key parameters, including acidification duration, acid concentration, and the variance in in-situ stress coefficients, on the rock pressure curve and fracture morphology.

Table 1. Experimental parameter design

Sample number	In-situ stress	Stress difference coefficient	Mode	Acid concentration	Acidification time
No.W-1	σ_H =15, σ_h = 7, σ_v = 20	σ_H~ σ_h = 1.14, σ_v~ σ_h = 1.85	Hydraulic fracturing	–	–
No.A-1	σ_H =15, σ_h = 7, σ_v = 20	σ_H~ σ_h = 1.14, σ_v~ σ_h = 1.85	Acid fracturing	20% HCI	2 minutes
No.A-2	σ_H =15, σ_h = 11, σ_v = 20	σ_H~ σ_h = 0.36, σ_v~ σ_h = 0.81	Acid fracturing	20% HCI	10 minutes
No.A-3	σ_H =15, σ_h = 11, σ_v = 20	σ_H~ σ_h = 0.36, σ_v~ σ_h = 0.81	Acid fracturing	20% HCI	30 minutes
No.A-4	σ_H =15, σ_h = 11, σ_v = 20	σ_H~ σ_h = 0.36, σ_v~ σ_h = 0.81	Acid fracturing	20% HCI	60 minutes
No.A-5	σ_H =15, σ_h = 11, σ_v = 20	σ_H~ σ_h = 0.36, σ_v~ σ_h = 0.81	Acid fracturing	9% HCI	10 minutes
No.A-6	σ_H =15, σ_h =11, σ_v = 20	σ_H~ σ_h = 0.36, σ_v~ σ_h = 0.81	Acid fracturing	36% HCI	10 minutes
No.A-7	σ_H =15, σ_h = 9, σ_v = 20	σ_H~ σ_h = 0.66, σ_v~ σ_h = 1.22	Acid fracturing	20% HCI	10 minutes

Experimental result

Breakdown pressure

We investigate the influence of acidification conditions on the pressure behavior of high temperature carbonate rocks. The curve's horizontal axis represents time, whereas the vertical axis corresponds to the outlet pressure, as shown in fig. 2.

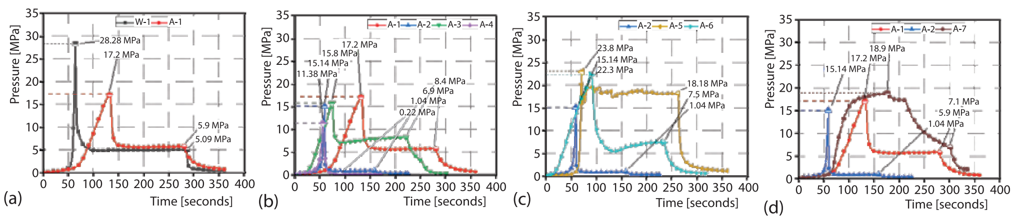

Figure 2. The breakdown pressure curves resulting from eight distinct experimental groupings; (a) acidification on the fracture curve, (b) influence of acidification duration on the fracture curve, (c) influence of different acid concentrations on the fracture curve, and (d) role of stress

The primary comparison group of No.W-1 is hydraulic fracturing. It displayed the highest breakdown pressure, measuring 28.28 MPa. Notably, A-4 had a breakdown pressure of 11.8 MPa, which was 16.48 MPa lower than that of No.W-1. This difference amounts to a 58% decrease. In the borehole, soluble particles react with hydrogen ions, results in forming irregular corrosion grooves, wormholes, and microfractures. Thus, this process effectively reduces breakdown pressure. Furthermore, as shown in fig. 2(b), extending the acidification duration affects the breakdown pressure within the rock strata. Although this reaction can reduce the rock surface's skin coefficient, it necessitates an extended contact period for the acid to reach the inner mineral particles of the rock to increased dissolution area.

As shown in fig. 2(c), acid concentration have little effect on the rock's breakdown pressure. And as shown in fig. 2(d), the horizontal stress coefficient difference was maintained between 0.36-1.14. However, no systematic trend was observed in the breakdown pressure.

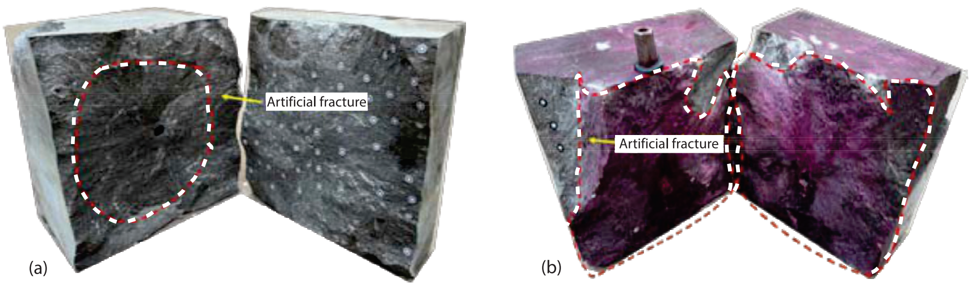

**Figure 3. Fracture morphology of carbonate rock;
(a) un-acidizing treatment of the fracture and (b) acidizing treatment of the fracture**

Fracture morphology

Exploration of fracture surface morphology during our experimentation, and coloring fractures is more conductive to the capture of artificial crack morphology, fig. 3. Visualize the eight sets of experimental results by using this method, fig. 4, demonstrated a predilection of hydraulic fracturing for single, short-length extension fractures. Antithetically, acidification samples presented us with less simplistic and more intricate fracture morphology. Analysis unveiled acidification make fractures tortuosity increased and a pronounced deviation of fracture extension from the direction of maximum horizontal principal stress. The fracturing volume has been observed for increase acidification time.

To reduce in-situ stress's influence on fracture morphology, we applied the orthogonal experimental method for comparison with samples numbers No.W-1, No.A-1, and No.A-7. This pattern indicates that spatial irregularities in acid etching could influence the pore-structure within the rock, caused random propagation of factures extension. Finally, we further explored the impact of acid concentration on the experiment, as shown in fig. 4. It was performed with three groups: No.A-2, No.A-5, and No.A-6, analysis revealed acid concentration did not obvious effect.

Conductivity

This study introduces a specific concentration of hydrochloric acid into the artificial fractures for acid treatments. Henceforth, this process will be known as acid treatment. It is vital to conduct injection pumping tests under in-situ stress conditions, effectively compare changes in fracture conductivity during acid treatment. This procedure produces a second outlet pressure

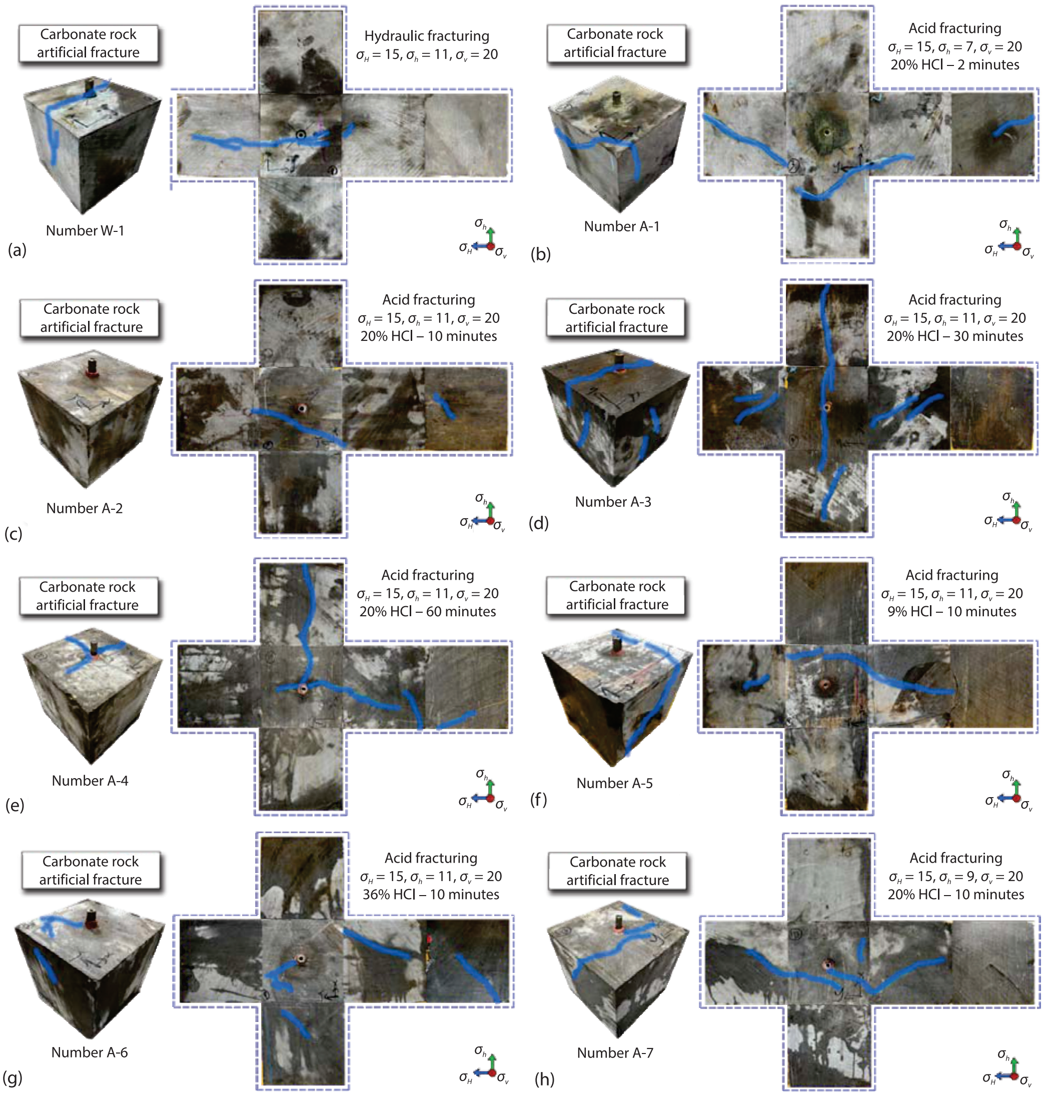

Figure 4. Fracture morphology of different experimental conditions

curve, which represents the post-acid treatment fracture pressure profile. The conductivity of the fractured material can be indicated by the permeability coefficient. An increased permeability coefficient indicates decreased seepage resistance and enhanced fracture conductivity. There is a negative correlation between the outlet pressure values from the two injection pumping tests and the permeability coefficient. As the outlet pressure value decrease, the permeability coefficient follows suit, resulting in enhanced fracture conductivity [9].

Comparison of conductivity after acidification and no-acidification, experimental results show a relatively stable pressure curve after acidification, in which No.A-1 and No.A-2 preserving the fluid-flow inside the fracture. Contrast, W-1 exhibits oscillating fluctuations present in its curve. Illustrated in fig. 5(a), clearly shows that the steady-state pressure following acidification is lower than the amplitude of pressure fluctuations seen during hydraulic fracturing. Furthermore, extended acidification time is observed to cause a significant drop in the constant pressure value. Considering these phenomena, we can delve into the first issue the fluctuation in the pressure curve during hydraulic fracturing of No.W-1. The instability of the pressure curve is likely due to fracture closure. For No.W-1's pressure curve, no proppant is utilized and triaxial stress is evident. Consequently, the fracture initially closes under stress-induced effects, but continuous fluid pumping reopens it. Lower outlet pressure appears due to increased acidification time, as fig. 5(a). Enhancing the duration of acidification can indeed promote better dissolution of the acid solution the rock, facilitating the formation of a more roughened fracture. The increase of roughness makes fractures worse to closure, resulting the conductivity improve. Moreover, altering the acid concentration can also improve the performance of acid fracturing. In fig. 5(b), the No.A-5 acid concentration is at 9%, with the peak value of the pressure curve during the pump injection remaining relatively high. Conversely, acid concentrations of 20% and 36% correspond to smaller peak values of the acid pressure. This suggests that acids of higher concentration can efficiently heighten fracture conductivity. This is because solutions with high acid concentration contain a larger count of hydrogen ions, which can further deplete soluble mineral particles in the rock, augmenting the self-sustaining effect. Subsequently, comparison of the conductivity after acid treatment, fig. 5, illustrates the pressure test results. Upon analysis of the experimental findings, acid treatment makes a consistently low pressure value. Analysis acid treatment can decrease the degree of closure between the surface and the surface.

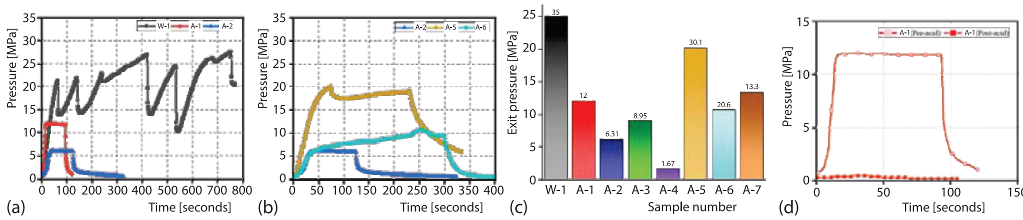

Figure 5. Pressure-time curves under fracture seepage; (a) and (b) fracture seepage curve after fracturing, (c) pressure value derived from seepage in eight separate fracture experiments, and (d) fracture seepage curve before and after acid treatment

Roughness scanning of fractures is our next work, fig. 6. The scan results reveal a significant increase in surface roughness for fractures after acid treatment. The increased roughness suggests a greater degree of surface irregularities, resulting in the formation of more microscopic pores and fractures. This amplification of the fluid-flow path improves the flow state and enhances reservoir permeability. In the case of acid fracturing on high temperature carbonate rocks, the post-treatment fracture displays outward diffusion from the wellbore, char-

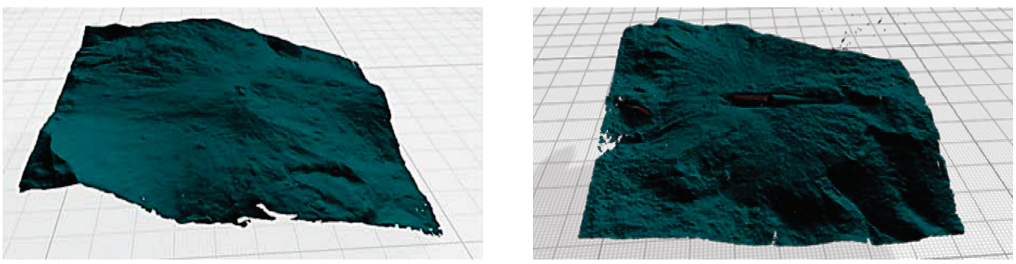

Figure 6. The constant pressure value of pressure curve in pump injection

acterized by striations and particulates. This irregular etching creates a fracture with a unique shape that is difficult to close under stress conditions, thereby increasing fracture stability. Further analysis indicates that the flow distance of acid within the fracture, particularly the acid etching area, is a crucial evaluation parameter. Traditionally, acid fluid-flows unidirectionally in dynamic rock plate acid etching experiments. Non-etheless, under triaxial stress conditions, the acid etching area within the fracture displays planar bidirectionality.

Conclusion

In this study, we examined the effects of acidification and subsequent acid treatment on the fracture behavior of high temperature carbonate rocks during acid fracturing. A significant 58% reduction in maximum fracture breakdown pressure was observed in acidification experiment that compared to hydraulic fracturing. Increasing acidification time primarily strengthen this effect, whereas the acid concentration has no significant impact on the breakdown pressure.

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