Parameter-Variable Experiments for Conductivity of Acid Etched Fractures

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Abstract: Conductivity of acid etched fractures is the decisive factor of results of acidizing treatment. At present, tests for etched fracture conductivity are in all cases executed using fresh acid under fixed experimental conditions, which determines that the test results can only capture fracture conductivity of the near-wellbore zone. This paper investigates fracture conductivity in cases of varied acid concentrations, temperatures, fracture widths and flow velocities along the fracture length direction, via the parameter-variable experiment for fracture conductivity. Results show that the combined changes of acid concentrations, fracture widths and injection rates have considerable impacts upon the conductivity distribution of etched fractures along the fracture length. Maximum etched fracture conductivity occurs within a certain distance from the wellbore. Variation of acid concentration along the fracture length is the main reason for changes in fracture conductivity, while variations in fracture widths and acid flow velocities may greatly reduce the effective etching length of the etched fracture.

1. Introduction

Acid fracturing is one of the most important production stimulation approaches for carbonate reservoirs, of which stimulation performance is mainly dependent on the effective extension and conductivity of acid etched fractures. At present, studies on acid fracturing focus on how to improve the effective affected distance of acid (by slowing down acid-rock reaction and decreasing acid leakoff) [1–4], and yet research on how to enhance etched fracture conductivity is less reported. Major flaws exist in either fracture conductivity calculation models and fracture conductivity test methods, which leads to certain blindness in acid fracturing design, with respect to how to optimize acid etched fracture conductivity via adjustments of the acid solution formulation and operation parameters.

Now, laboratory studies on etched fracture conductivity, in most cases, all use fresh acid. Nevertheless, in actual acid fracturing operation, except the near-wellbore fracture surface that mainly contacts and reacts with fresh acid, all other positions react with residual acid. Along the fracture length, acid viscosity, fracture width, temperature for acid-rock reaction and acid flow rate all change, besides tremendous variation of acid concentration. Such factors are in turn coupled with the acid-rock reaction process, and these two aspects affect each other. Changes in reaction conditions may result in variations of acid-rock reaction rates and controlling factors with different positions, and subsequently varied acid etching morphology of fracture surfaces and etched fracture conductivity[5-7]. In order to better comprehensively analyze impacts of these factors upon etched fracture conductivity, this paper proposes the parameter-variable experimental method to investigate acid etched fracture conductivity.
2. Selection of experiment parameters

Acid flow and reaction through fractures are an extremely complex process, which is closely related to the acid concentration, fracture width (fracture net pressures) and fracture temperature profile. For the purpose of identifying appropriate experiment parameters, first we determine the experiment parameter via calculation based on the three-dimensional acid-rock flow and reaction model and reasonable conversion, and the results are summarized in Table 1.

| Core Sample No. | Fracture Length /m | Fracture Width /mm | Acid Concentration /% | Fracture Temperature /℃ | Reaction Duration /min |
|-----------------|---------------------|--------------------|-----------------------|--------------------------|------------------------|
| 1# | 0-10 | 3 | 20 | 40 | 60 |
| 2# | 10-25 | 2 | 14 | 58 | 45 |
| 3# | 25-50 | 1.2 | 8 | 75 | 30 |
| 4# | 50-70 | 0.3 | 3 | 95 | 15 |

3. Experiment analysis

3.1. Instruments and reagents

Experimental instruments and reagents include: the acid etched fracture conductivity measurement apparatus, a high-precision balance (Shimadzu Corporation, Japan), gelled acid, limestone core samples (from Yangshuiku), and calcium carbonate (LR)

3.2. Experimental methodology

(1) Cut the core sample into the core sheets with required dimensions, which are then vacuumed and saturated with standard brine.

(2) Prepare gelled acid solution with required concentration.

(3) Turn on the heating jacket and heat the acid system.

(4) Place the core sheets into the flow chamber and seal them using elastomers, and adjust them to realize the desired fracture width.

(5) Inject acid solutions heated to the specified temperature into the flow chamber for acid-rock reaction.

(6) Stop acid injection, and clean the core sheets using fresh water immediately.

(7) Measurement fracture conductivity after acid etching.

(8) Disassemble and clean the apparatus.

4. Experimental results and discussion

4.1. Characterization of acid performance

Rheology of acid solutions plays an utmost role in the acid-rock reaction process. For example, variation of acid rheological properties alters flow status of acid on fracture surfaces, and change of acid viscosity affects diffusion of $H^+$. Therefore, we first test the rheological property of acid under varied experimental conditions, and the results are shown in Table 2.

| Acid Concentration /% | Temperature /℃ | Flow Index $n'$ | Consistency Factor $K'$ (Pa·sª) | Apparent Viscosity, mPa·s | 170 s⁻¹ |
|-----------------------|-----------------|-----------------|-----------------|----------------------|--------|
| 20                    | 40              | 0.591           | 0.455           | 54.2                | 48.5   |
| 14                    | 50              | 0.613           | 0.354           | 48.5                | 36.9   |
| 8                     | 75              | 0.628           | 0.249           | 36.9                | 27.4   |
| 3                     | 95              | 0.682           | 0.141           | 27.4                |        |
4.2. Experimental investigation of fracture conductivity
The acid etched fracture conductivity experiment is carried out in accordance with the experiment parameters in Table 1. In order to validate repeatability of experiment results, three tests are conducted for each group of experimental conditions. In the meantime, it is required that the core sheet for experiments should, to the greatest extent, be collected from the same full-diameter core sample, so as to avoid experiment data errors induced by lithology and physical property heterogeneity of reservoirs.

Figure 1. Photo of core samples after acid-rock reaction under the #1 experiment conditions

The etched fracture conductivity at the fracture entrance is first measured. Fig. 1 presents representative acid etching morphology of the core sample. It is seen that the core surfaces are etched irregularly by acid. The dissolved volume is larger at the core entrance, and is smaller in the middle area. Experiments show that fresh acid still has strong destructive effects upon core samples, although the experiment temperature is relatively low. After the fracture conductivity measurement, the core sample is destructed by compressing under high closure pressures. This indicates that besides pursuing the dissolution volume and irregular etching, acid fracturing shall also consider maintaining rock mechanics properties of the formation, and how to maintain fracture conductivity for longer time in this core area shall be a key point in acid fracturing design.

Figure 2. Photo of core samples after acid-rock reaction under the #2 experiment conditions

Fig. 2 demonstrates that in the #2 experiments, the whole rock surface is irregularly etched by acid, and a relatively deep etched channel is created. Such etching morphology can result in high fracture conductivity. Although in these experiments, the acid concentration and injection rate are reduced, elevated temperatures together with reduction in fracture width are in favor of improving dissolution of core samples. It is also found that strength weakening induced by this acid is lower than that of fresh acid, and the core sheets stay intact after fracture conductivity testing, which is key to maintaining fracture conductivity under high closure pressures.

Figure 3. Photo of core samples after acid-rock reaction under the #3 experiment conditions

The dissolution volume of core surfaces is apparently smaller in the #3 experiments (Fig. 3).
Irregular etching of core surfaces is still formed in local areas, and yet dissolved zones have poor connected and limited contributions to fracture conductivity, due to small dissolution volumes. The low-concentration acid results in smaller strength reduction of the core sheets, which still maintain intact after fracture conductivity testing. This is favorable for keeping fracture conductivity under high closure pressures. After comprehensive consideration, it is believed that the major factor affecting fracture conductivity in this core area is the rock dissolution capacity of acid, and thus retarded acid shall be used to slow down acid-rock reaction, increase the dissolution volume and enhance fracture conductivity in this core area.

Figure 4. Photo of core samples after acid-rock reaction under the #4 experiment conditions

Fig. 4 presents that although the experiment temperature in the #4 experiments reaches 95°C, except the core entrance is seen with partial dissolution, other areas almost have no change, due to extremely low acid concentration together with the common-ion effect and low acid injection rate. This suggests the resultant etching morphology can hardly provide effective fracture conductivity under high closure pressures, due to low dissolution capacity, and the fracture in this area is basically ineffective, even though acid is still able to dissolve rock.

Figure 5. Etched fracture conductivity

The maximum fracture conductivity occurs at the position within certain distance from the near-wellbore zone, where the formation temperature is favorable for acid-rock reaction and the acid concentration, lower than that of fresh acid, is able to reduce rock strength weakening induced by acid and in favor of maintaining conductivity under high closure pressures. In areas farther away from fractures, relatively higher fracture conductivity can be maintained under high closure pressures, due to lower strength weakening induced by acid, although the rock dissolution volume in this area is less than that at the fracture entrance and the fracture conductivity in this area is indeed lower than that at the fracture entrance in the case of low closure pressures. Due to extremely limited fracture opening at the fracture tip, acid-rock reaction is similar to closed acidizing. Nevertheless, owing to small dissolution volumes of fracture surfaces attributed to low acid concentration, the fracture tip barely has conductivity under high closure pressures.

Experiments show that under the joint effects of the acid concentration, fracture width and acid flow rate, the actual effective stimulated distance of acid etched fractures is tremendously different from the calculation result in the acid fracturing model according to the effective acid concentration variation. Well testing and production history matching after field practice of acid fracturing also confirm our observation. Therefore, it is safe to conclude that the approach frequently-adopted in
oilfields to determine the effective stimulated distance of acid etched fractures by acid concentration is to some extent unreasonable, and the fracture length actually contributing to hydrocarbon flow in reservoirs shall be lower than the effective stimulated distance of etched fractures.

To further investigate the effects of acid concentration variation upon fracture conductivity, the conductivity of fractures etched by fresh acid is measured with all the other conditions (temperature, fracture width and injection rate) identical to those in the #2 experiments.

As the acid concentration and reaction temperature grow, core surface dissolution induced by acid increases, width of etched grooves expands and supported areas of fractures narrow, which may impact maintaining of fracture conductivity. Moreover, rock strength weakening after fresh acid reaction is great, and core samples fail after conductivity testing. It is seen from Fig. 6 that the core sheets maintain relatively high conductivity under low closure pressures after reacting with fresh acid; yet, the acid etched fracture conductivity presents a higher decline rate than that of the core sheets reacting with low-concentration acid, as closure pressures climb up. This demonstrates that under low closure pressures fracture conductivity is related to etching morphology, while it is more dependent on the compressive strength at the contact point under high closure pressures.

5. Conclusions and suggestions

(1) The combined variation of the acid concentration, fracture width and reaction time has great impacts upon conductivity of acid etched fractures along the fracture length. Thus, conductivity variation along the fracture length shall be incorporated in acid fracturing simulation.

(2) The parameter-variable etched fracture conductivity experiment indicates that along the fracture length, the maximum fracture conductivity occurs at the position with certain distance from the wellbore, instead of at the near-wellbore zone.

(3) Acid concentration variation along the fracture length, which mainly affects the acid-rock reaction rates and induced rock strength weakening, is the major contributor to acid etched fracture conductivity alteration along the fracture length.

(4) Variations of fracture width and acid flow rate distributions along the fracture length may lead to the effective stimulated distance of etched fractures longer than the length calculated using the acid fracturing model according to effective acid concentration variation.

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