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Investigation on acid fracturing treatment in limestone formation based on true tri-axial experiment

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ABSTRACT

Acid fracturing treatment is the most effective method for stimulating limestone formations, which are abundant in the northeast Sichuan basin of China. The effective acid etching improves the fracture width, resulting in high fracture conductivity, while fracture propagation behavior is always affected by discontinuities and the fractured vuggy structure. Hence, the fracture geometry differs from that in homogeneous formations. However, the fracture propagation mechanism remains unclear. In order to understand the process more clearly, a series of large-scale, true tri-axial simulation experiments were conducted for the first time to investigate the fracture initiation and propagation in limestone formations under acid fracturing treatment. Moreover, the effects of multiple factors on fracture propagation were discussed, and a 3D scanner was used to depict and describe the fracture surface etching feature. The experimental results demonstrated that natural fractures had a serious impact on the fracture initiation and propagation. The induced fracture initiated from the open-hole section to form a transverse fracture, or from the natural fractures to form a longitudinal or an inclined fracture. The fracture surface was rougher in the acid fracturing than in hydraulic fracturing, owing to the non-uniform acid fluid dissolution. The black-brown remains on the fracture surface were the result of acid etching, which could be used to judge the fracture propagation direction and area. However, the roughness degree of the fracture surface near the wellbore was larger than that far from the wellbore. Furthermore, HCL fluid was likely to etch the fracture surface within a short propagation distance, while clean-acid fluid promoted induced fractures to propagate at a long distance. Furthermore, a slow decrease in the extension pressure in the fracture curve indirectly indicated that the acid fluid reacted with the matrix and propagated slowly, which was a sign of successful acid fracturing treatment. According to the experimental results, the acid etched width and fracture propagation distance are assumed to be two important factors for estimating the acid fracturing treatment performance.

1. Introduction

Limestone formations are rich in northeast Sichuan, and possess low porosity and permeability, which requires hydraulic fracturing to stimulate production. The stimulated reservoir volume (SRV) is an effective method for the commercial development of unconventional formations. It improves natural fracture expansion and induces shear slip during the fracturing process [1]. Natural and artificial fractures form a complex fracture network to allow oil and gas with increased channels to flow into the wellbore. Single well productivity and ultimate recovery can be enhanced by SRV, which has been applied successfully in shale and coal formation stimulation [1–3]. However, the majority of slick-water lost in fractured or cavernous structures result in a failed SRV when limestone formation is stimulated by means of traditional hydraulic fracturing treatment [4]. Hence, acid fracturing treatment has been developed and has become an essential and indispensable method for stimulating limestone formation.

The matrix and fracture walls are under non-uniform acid fluid etching, resulting in surface roughness, which creates lasting conductivity following induced fracture closure [5,6]. However, the fracture conductivity is dependent on the different surface etching patterns. Mou et al. [7] believed that the permeability and mineralogy distributions in limestone formations determine the surface etching patterns. Deng et al. [8] discussed the concept of closure stress affecting the conductivity change rate. Oeth et al. [9] claimed that the acid etched width has an impact on conductivity. Moreover, Aljawad et al.

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[10] indicated that different acid fluid systems should be selected according to the formation feature for improved fracture conductivity. Successful acid fracturing treatment requires not only high fracture conductivity, but also a long acid penetration distance. However, fracture propagation behavior is complex in heterogeneous formations [11–13], owing to the existence of discontinuities such as natural fractures, bedding planes, joints, and calcite veins, as opposed the simple bi-wing fracture in homogeneous sandstone formations [14]. Numerous scholars have studied the influence of discontinuities on fracture propagation. Warpinski and Teufel [15] observed that an induced fracture could penetrate, deflect, and arrest these discontinuities, according to different natural and engineering factors. Teufel and Clark [16] proved that the fracture preferred to divert into discontinuities with a low friction coefficient and low interface cohesion. Zhou et al. [17] highlighted that the shear strength of pre-existing fractures determines the induced fracture propagation behavior. Liu et al. [18] found that the induced fracture crossed the pre-existing fracture under a high horizontal stress contrast and large pre-existing fracture angle, and maximum horizontal stress in carbonate formations. Lee et al. [19] implied that the approach angle and vein thickness also affect the fracture propagation. Furthermore, SRV requires induced fractures to activate numerous discontinuities in order to form a complex fracture network. Rickman et al. [20] confirmed that a complex fracture network is created during the formation, with a high brittle mineral content and low clay mineral content. Olsen et al. [21] examined the fact that shale formation with a low Poisson's ratio and extremely low permeability promoted the generation of a complex fracture network. Moreover, engineering factors such as the fluid viscosity and injection rate could be controlled and adjusted to enhance the interaction between the induced fracture and discontinuities, resulting in a large SRV. Kresse et al. [22] revealed that the fracture crosses discontinuities at a high injection rate, while it offsets and deflects those at a low injection rate. Cipolla et al. [23] clarified that high viscosity fluid creates a main fracture, while low viscosity fluid activates discontinuities.

Prior studies have mainly focused on fracture conductivity following acid fracturing treatment or hydraulic fracture propagation behavior in shale outcrops and cement stones. Although several researches have been conducted on limestone outcrops [4,18,24], the point of concern point was always hydraulic fracture rather than acid-etched fracture. Little attention has been paid to acid etched fracture propagation behavior in limestone formations, which should present a different scenario owing to the special physical and tectonic characteristics of limestone formations. The cavern system is a common structure in limestone formation, which affects induced fracture propagation. The hydraulic fracture crosses these caverns from inside, where the weakest rock strength exists. Acid fluid, however, reacts with the cavern wall to reduce the rock strength, resulting in numerous weak rock strength points for the acid-etched fracture to cross. However, the propagation mechanism of acid etched fracture remains unclear.

In this study, four large true tri-axial acid fracturing simulation experiments were conducted to investigate the initiation and propagation of acid-etched fractures in limestone formations for the first time. Moreover, the effects of the acid fluid type and number of perforation clusters on the propagation behavior of acid-etched fractures were investigated. Our research findings provide insight into the initiation and propagation of acid-etched fractures, and offer effective guidance on acid fracturing treatment in limestone formations.

2. Experimental process and scheme

2.1. Experimental apparatus

All experiments were conducted in an improved true tri-axial pressure machine, as illustrated in Fig. 1, consisting of a true tri-axial test frame, confining pressure loading system, servo control system, and data acquisition and processing system. A 400 mm cubic sample was placed in the test frame and surrounded by flat jacks that applied a confining pressure with a maximum output of 30 MPa. The flat jacks were the same size as the sample surface in order to ensure uniform pressure. The injecting acid fluid container was made from acid-proof Babbitt metal with a maximum injection volume of 800 mL. The maximum injection pressure of 140 MPa was maintained by the servo control system.

2.2. Sample preparation

The horizontal wellbore, including a wellhead and chamber, was constructed from Babbitt metal, as illustrated in Fig. 2b. The wellhead had a length of 40 mm, an outer diameter of 14 mm, and an inner diameter of 8 mm. The chamber had a length of 120 mm, an outer diameter of 10 mm, and an inner diameter of 8 mm. Furthermore, a circular tray with a radius of 30 mm and thickness of 20 mm, and several circular columns, were installed on the wellhead and chamber, respectively. These additional designs prevented the fracturing fluid from flowing from the well bottom to the wellhead along the narrow annulus between the wellbore and borehole under a high pressure with ineffective cementing. Otherwise, this phenomenon could cause the experiment to fail and would be dangerous to the experimenters.

The limestone samples were collected from the Feisanduan limestone formation in northeast Sichuan, and were cut into $40 \times 40 \times 40$ cm cubes using wire cutting technology, as illustrated in Fig. 2a. A deep hole with a radius of 10 mm and depth of 270 mm (120 mm for the horizontal wellbore and 150 mm for the open-hole section) was drilled in the center of the cubes to simulate the borehole, as illustrated in Fig. 2b. In order to simulate the perforated fracturing, which improves oil production [25], several symmetrical deep slots with a width of 2 mm and depth of 5 mm were cut on the walls of the open-hole section. Two slotting methods simulate different perforation clusters: two and three clusters of perforated fracturing, respectively, as illustrated in Fig. 2c and d. Subsequently, the wellbore was fixed inside the borehole with foam filler and high-strength epoxy glue, as indicated in Fig. 2b. The average tri-axial mechanical parameters of certain cylindrical cores were measured as follows: compressive strength: 270.5 MPa; elastic modulus: 42.1 GPa; and Poisson's ratio: 0.32. The mineralogical composition was analyzed using X-ray diffraction. The average carbonate, quartz, and clay contents were 89%, 1.55%, and 2.93%, respectively.

Discontinuities, such as stylolite structures, calcite veins, and natural fractures, which are common and widely developed geological structures, have a significant impact on fracture initiation and propagation. Therefore, it is vital to determine the number and distribution of discontinuities in the limestone samples prior to fracturing. In order to describe the discontinuities clearly in each limestone sample, the sample surfaces were defined as follows: P1 and P6 represented the upper and lower surfaces, P2 and P5 represented the front and back surfaces, and P3 and P4 represented the right and left surfaces, respectively. As an example, illustrated in Figs. 3 and 4b, limestone sample #2 contained several well-developed natural fractures on surfaces P2, P3, P4, and P5, as well as some calcite veins on surfaces P1, P3, and P6. Moreover, certain obvious caverns were identified on surfaces P3, P4, and P6. A 3D schematic diagram of sample #2 was drawn, as depicted in Fig. 4b, to clarify these discontinuities. All discontinuities in each limestone outcrop are summarized in Table 1 and depicted in Fig. 4. Well-developed discontinuities are a result of slick-water leakage, which results in failed fracturing.

2.3. Experimental scheme

The depth of the Feisanduan limestone reservoir in northeast Sichuan is 4775–4872 m under a normal-faulting stress regime: vertical stress of 94.17–123.92 MPa, maximum horizontal stress of 76.65–95.45 MPa, and minimum horizontal stress of 72.05–87.03 MPa.