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LABORATORY STUDIES OF FRACTURE GEOMETRY IN MULTISTAGE HYDRAULIC FRACTURING UNDER TRIAXIAL STRESSES

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We present the results of a laboratory experiment on multistage hydraulic fracturing using a gel solution as the fracturing fluid, utilizing a laboratory setup for simulating hydraulic fracturing under triaxial stresses. As a result of the experiment, a fracture network was formed in a cubic rock specimen. We found that an almost planar fracture was formed during the first fracturing stage, while a concave (bowl-shaped) fracture was formed during the second stage. Interaction between the stress fields created by the two main hydraulic fractures (stress interference) caused growth of secondary cracks parallel to the simulated wellbore, but in this case led to a decrease in the width of the subsequent main fracture. We established that the penny-shaped fracture model is more suitable for predicting the geometry of hydraulic fractures in horizontal wells than two-dimensional (rectangular) fracture propagation models (the Perkins – Kern – Nordgren (PKN) model, the Khristianovic – Geertsma – de Klerk (KGD) model). Special attention needs to be paid to fracture spacing design in multistage hydraulic fracturing in horizontal wells.

Key words: *hydraulic fracturing, hydraulic fracture, horizontal well, fracture geometry, hydraulic fracture spacing.*

The horizontal segment of a horizontal well is usually drilled parallel to the horizontal minimum *in-situ* stress and generally the horizontal segment is fractured in multiple hydraulic fracturing stages, carrying out

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one stage at a time, starting from the toe. As a result of multistage hydraulic fracturing, several transverse fractures are initiated. Today, in order to achieve the best economic indicators for production, optimization of fracture parameters is based on optimization of fracture number and fracture length. Fracturing spacing also significantly affects production, and this parameter should be optimized to maximize hydrocarbon rate and reservoir drainage.

The complexity of hydraulic fracture geometry has become more and more obvious due to widespread application of improved fracture diagnostic technology [1]. Artificially created hydraulic fractures and pre-existing fractures can interact, and this interaction is a key factor explaining the complex behavior of fracture propagation [2]. Each open fracture creates an additional stress field acting on the surrounding rock and adjacent fractures, which is called "stress shadow" [3, 4]. "Stress shadow" can strongly affect the fracture width and path (its orientation in space), which to a significant extent restricts spreading of proppant and the fracture network system. Increasing fracture spacing can weaken stress perturbation [5-7] and thus can help avoid intersection of subsequent fractures with the previous fractures [8]. But in this case, more transverse fractures promote higher initial production rates and presumably better drainage in low-permeability reservoirs.

Based on an improved 2D displacement discontinuity method with correction for finite fracture height, Wu [3] and Cheng [9] proposed a method for calculating the "stress shadow" in a complex fracture network. Such parameters as the ratio of minimum to maximum horizontal *in-situ* stress, Poisson's ratio, Biot's coefficient, and the net fracture pressure, which to some degree affect fracturing spacing, were studied in [4] by the finite element method. In order to determine the key parameters which can affect fracture reorientation, we used dimensional analysis and a scaling method. A subsequent fracture will either curve toward a previous fracture or away from it (attractive or repulsive) [10]. Low *in-situ* stress anisotropy, caused by the stress contrast due in turn to net fracturing pressure, increases the chance of reorientation of a subsequent fracture [3, 4, 7, 11]. The turning angle of the maximum horizontal principal stress can be calculated for determining the optimal fracturing spacing to avoid drastic deviation during fracture propagation. Compared with consecutive hydraulic fracturing, alternative fracturing and simultaneous fracturing make it possible to shrink the stress-reorientation region [12]. In consecutive hydraulic fracturing, in order to achieve acceptable stress interference, the subsequent fracture spacing should be greater than previous fracture spacing [6].

However, the adequacy of the theoretical models listed above, proposed for determining the fracture geometry and the fracturing spacing in multistage fracturing, has not been experimentally proven. In this

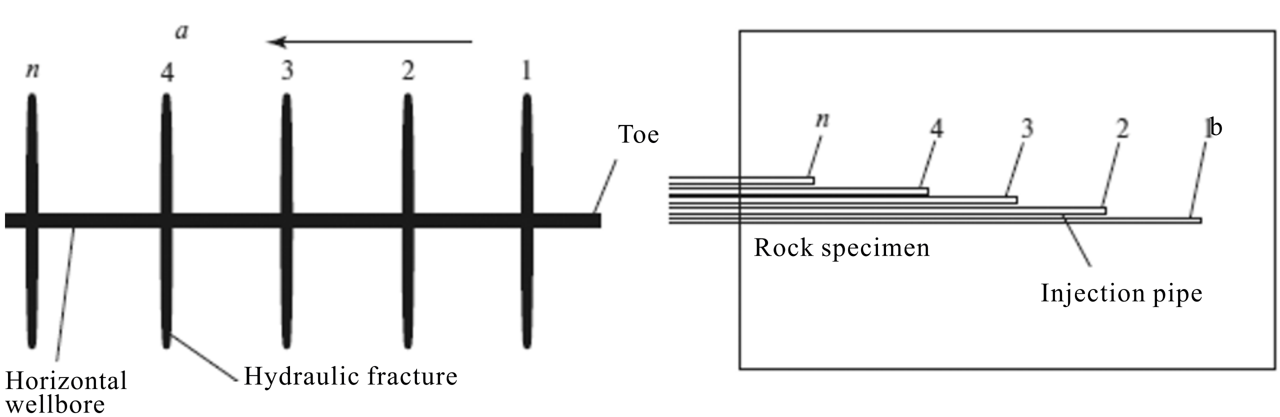

Fig. 1. Schematic drawing of consecutive hydraulic fracturing (*a*) and hydraulic fracturing simulated in the laboratory (*b*).

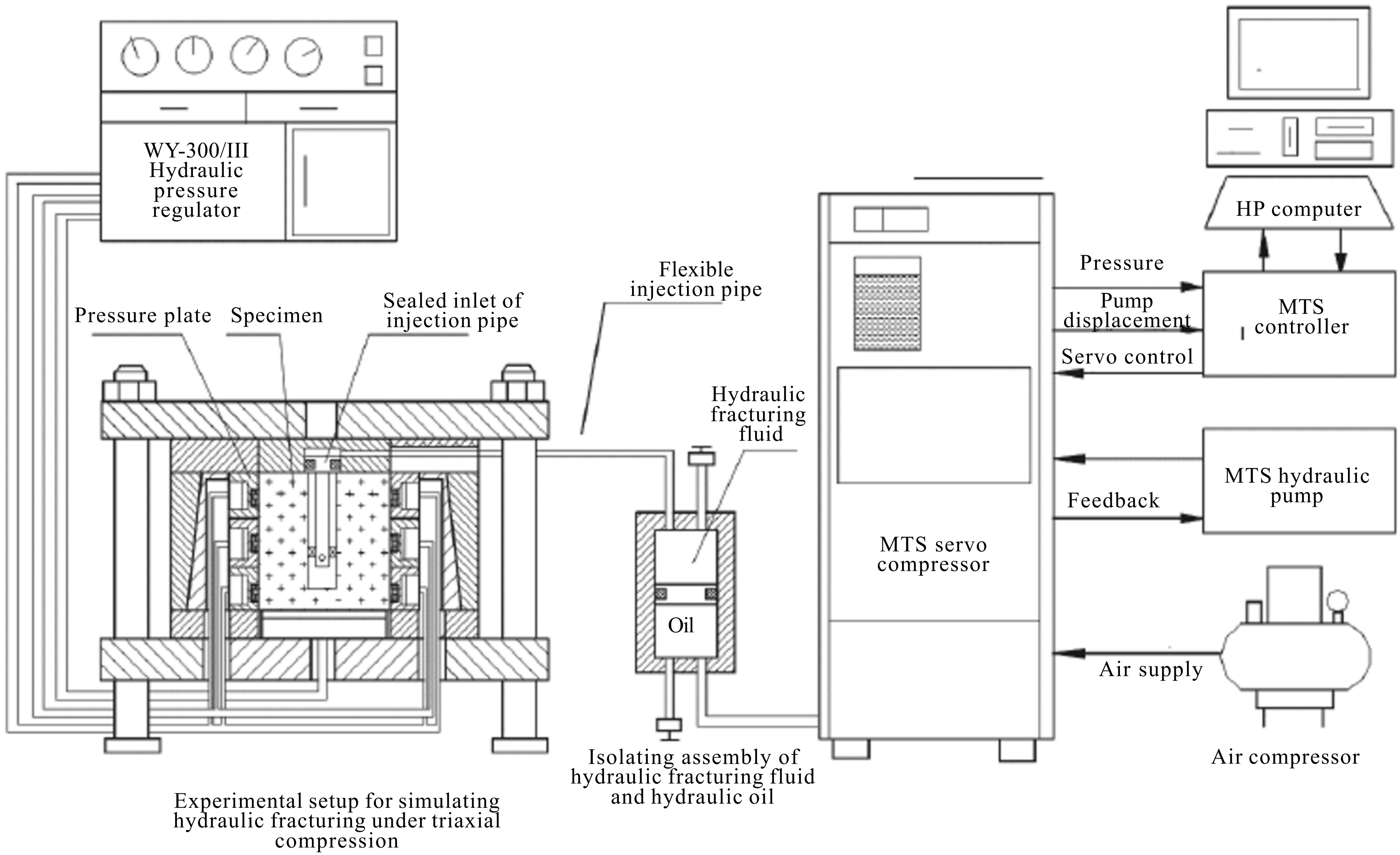

Fig. 2. Experimental setup for simulating hydraulic fracturing under triaxial stresses.

paper, we present the results of laboratory studies of multistage hydraulic fracturing using a gel solution as the fracturing fluid, conducted on a setup for hydraulic fracturing under triaxial stresses.

The horizontal segment of a horizontal well is drilled parallel to the horizontal minimum *in-situ* stress and generally is hydraulically fractured in several stages, carrying out one fracturing stage at a time, starting from the toe, i.e., consecutive fracturing. After multistage hydraulic fracturing in the selected formation, several (from 1 to n) transverse fractures are initiated.

Figure 1a and Fig. 1b respectively show schematic drawings of consecutive hydraulic fracturing *in-situ* and in the laboratory. In the second case, the fracturing fluid is sequentially injected into the specimen through injection pipes (numbered 1 to n) until fracture occurs and transverse fractures are formed at the end of the pipes, where the transverse fractures are perpendicular to the injection pipes in the specimen. The depth of the pipes in the specimen can be controlled during fabrication of the specimen for physical simulation of multistage fracturing with different spacings. Furthermore, the order of injection of the fracturing fluid into the pipes also can be controlled, thus simulating alternative fracturing. In this experiment, due to the limited specimen size, we carried out only two fracturing stages.

The experiments were conducted on a triaxial hydraulic fracturing system at China University of Petroleum (Beijing). Figure 2 shows a schematic drawing of this setup.

A cubic rock specimen was placed between steel plates, and the normal stresses created were respectively controlled by three pumps. The maximum confining stress in the system can reach 28 MPa. The hydraulic fracturing fluid injection pressure can reach 140 MPa using an MTS 816 hydraulic pump. A gel solution containing a yellow tracer was used as the fracturing fluid.

As shown in Fig. 3, the experimental specimen was a $300 \times 300 \times 300$ mm cubic concrete block in which two injection pipes were set at different depths during casting. The cement (R.S32.5) and the quartz sand (40–80 mesh) were mixed in 1:1 proportion. The curing time was 10 days. The fracturing fluid was injected through the injection pipes, with outer and inner diameters equal to 3 mm and 2 mm respectively. The mechanical

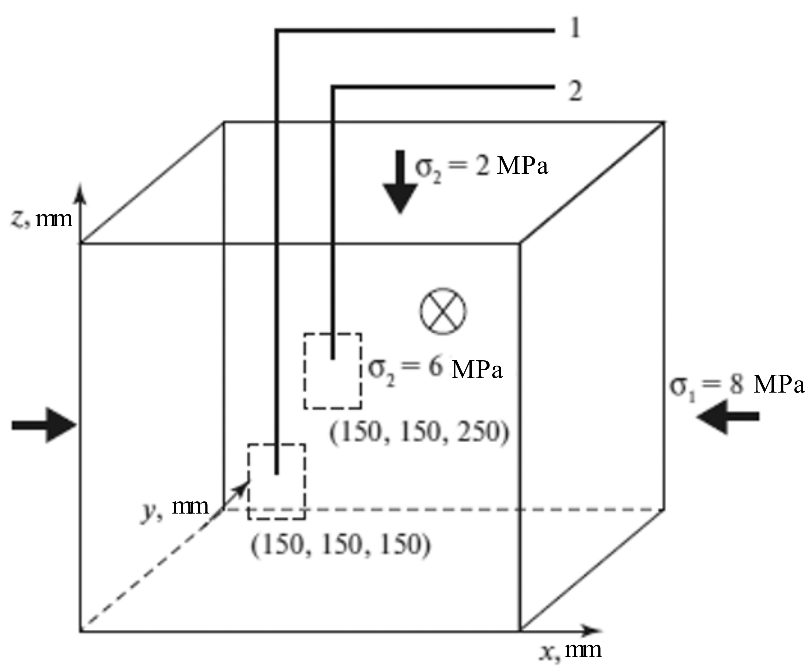

Fig. 3. Drawing of cement block.

properties of the specimen were as follows: elastic modulus, 8.4 GPa; Poisson's ratio, 0.23; uniaxial compressive strength, 28.34 MPa; cohesion of rock mass, 2.85 MPa; coefficient of internal friction, 0.75. The pump displacement was 0.2 mm/s for fracturing fluid viscosity 30 mPa·s. The *in-situ* stresses satisfied the condition $s_1 > s_2 > s_3$.

The experiment was conducted in the following sequence. First confining pressure was applied to the specimen using the confining pressure system. When the confining pressure reached the set value, the hydraulic pumps were used to begin injection of fracturing fluid into the specimen through the first injection pipe until the specimen fractured and the first hydraulic fracture was formed. Then the second injection pipe was connected to the hydraulic pump, and the second fracturing stage was carried out. Then the specimen was removed and photographs were taken.

Photographs of the hydraulic fractures for the two stages are shown in Fig. 4. We see that the first-stage fracture is initiated and propagates in the direction perpendicular to the minimum principal stress, and the fracture geometry is almost planar. At the same time, the second hydraulic fracture slightly deviates from the direction perpendicular to the minimum principal stress, and the shape of the fracture is a concave surface (bowl-shaped). In addition, the region of second-stage fracture propagation is a circle, which supports the theory that fractures in horizontal wells propagate within a circle, and so classical two-dimensional (rectangular) fracture propagation models (the Perkins – Kern – Nordgren (PKN) and Khristianovic – Geertsma – de Klerk (KGD) models) are not suitable for predicting hydraulic fracture geometry in horizontal wells. The yellowish green color in the first-stage hydraulic fracture was darker than in the second-stage fracture, which demonstrates that the first-stage fracture width is greater than the second-stage fracture width. The reason for this phenomenon is that the first-stage fracture compresses the specimen, and this load increases the stress in the direction of the *in-situ* minimum principal stress.

In addition, two secondary cracks (A and B) were formed parallel to the pipe as shown in Fig. 4*b*, which supports the theory of stress reorientation between the first-stage and second-stage hydraulic fractures. These fractures cause "stress shadow" (Ds), acting along the *in-situ* minimum principal stress. Hence after stress superposition, the new stress is s_F = Ds + s_3. If $s_F > s_2$, then the direction of the minimum stress is deflected by 90°, and secondary crack A is formed. As the stress shadow becomes larger, once the condition $s_F > s_3$ is satisfied then secondary crack B is formed.

Figure 4*c* shows the hydraulic fracture network. Figure 4*d* shows a small amount of the tracer in the fracturing fluid on the surface of the secondary crack, which indicates a small fracture width. Based on the shade of the tracer color on the fracture surface, we concluded the following about the widths of the fractures formed: $W_{F1} > W_{F2} > W_{CA} > W_{\mathrm{CB}}$, where W_{F2} is the width of the first-stage fracture; W_{F2} is the width of the second-state fracture; W_{CA} is the width of secondary crack A; W_{CB} is the width of secondary crack B.

Due to the limited size of the specimen that can be placed in the laboratory equipment, only two fractures were initiated. On the scale of the oil field, the number of stages for transverse fractures depends on the hydraulic fracturing equipment, the length of the horizontal segment, the perforation spacing, and other factors. The "stress shadow" created by the previous fracture can overlap the stress field created by the subsequent hydraulic fracture. It is implied that the widths of the main fractures in multistage hydraulic fracturing in horizontal wells, for the same fracture spacings, satisfy the condition $W_{F1} > W_{F2} > \ldots > W_{Fn}$. Reorientation of *in-situ* stresses in brittle rock between main fractures facilitates initiation of secondary cracks and formation of a fracture network (Fig. 5). Secondary cracks enable improved hydrocarbon conductivity, and their widths are smaller than the widths of the main fractures observed in the experiment described above. If the fracturing spacing is too small, then the main fractures may deflect (curve) and then

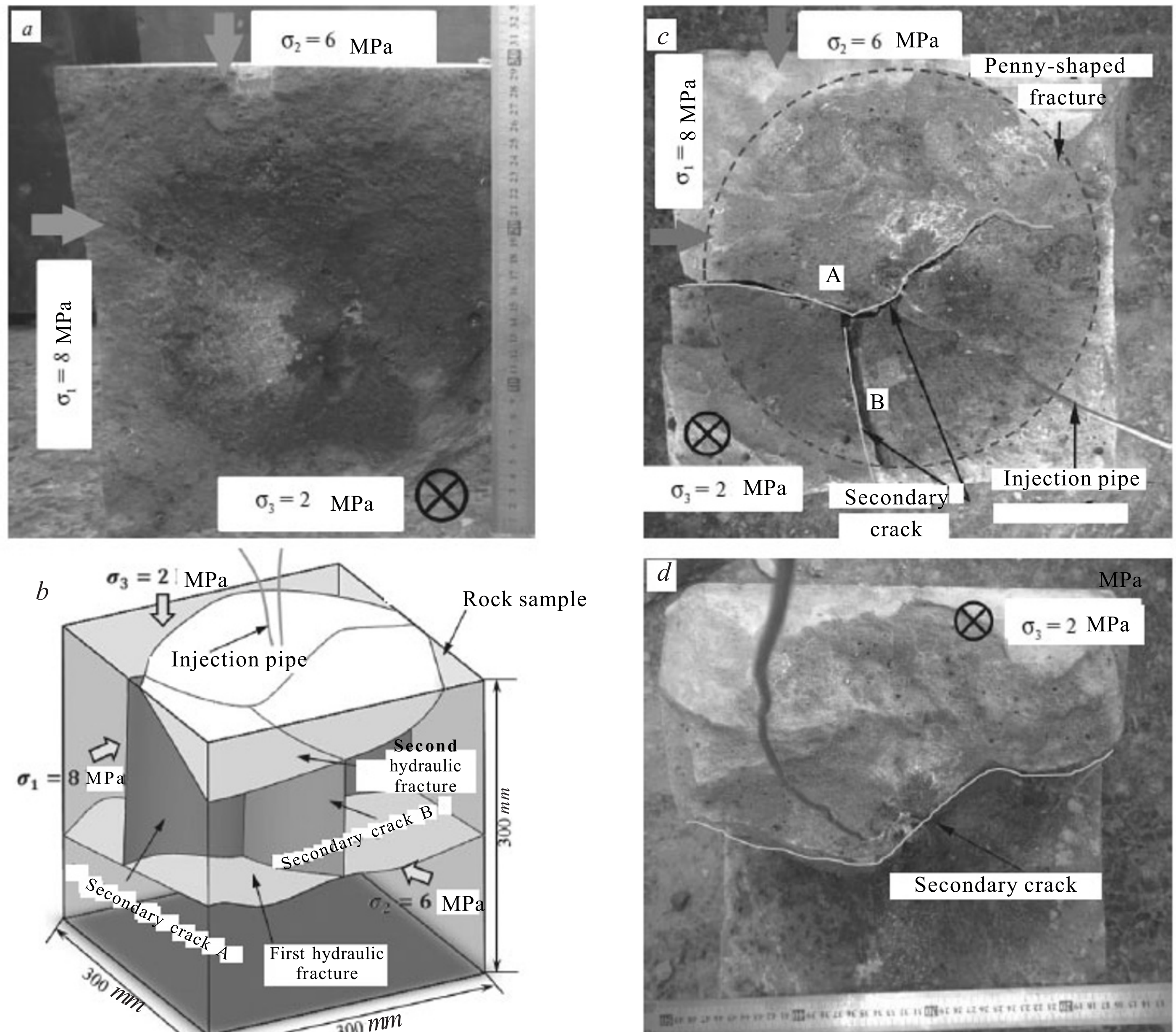

Fig. 4. Fracture geometry: *a*) first-stage fracture; *b*) second-stage fracture; *c*) overall view of specimen; *d*) top view of specimen.

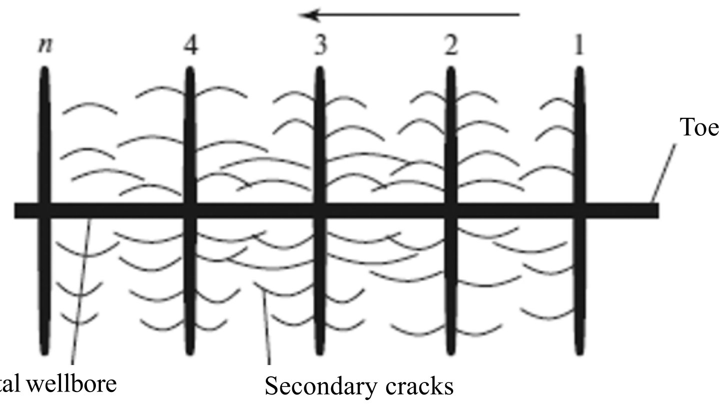

Fig. 5. Schematic drawing showing geometry of hydraulic fractures and secondary cracks.

connect with the previous fracture. This phenomenon can reduce the length of the main fractures and reservoir drainage. Therefore fracturing spacing should be optimized to maximize hydrocarbon rates and reservoir drainage for maximum hydrocarbon recovery [6].

Based on the results of our experiment, we drew the following conclusions:

If the fractures propagate only within a single formation during hydraulic fracturing, and their fronts do not reach the boundary of the formation, then the region of fracture propagation will always be a circle. The penny-shaped fracture model is more suitable for fracture geometry design in horizontal wells.

First-stage and second-stage hydraulic fractures are initiated and propagate along the direction perpendicular to the minimum principal stress. The first-stage fracture is approximately planar, while the second-stage fracture has a concave surface. This demonstrates the fact that the previous fractures have an effect on the geometry of subsequent fractures.

If the spacing between the fractures formed is too small, then stress interaction will lead to a reduction in the widths of subsequent fractures. First-stage and second-stage hydraulic fractures alter the stress field, which in turn will promote initiation of secondary cracks, propagating in other directions relative to the main fractures. From this we can conclude that in multistage hydraulic fracturing, we need to optimize the fracture spacing during design of the process.

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