An experimental investigation on the influence of temporary plugging fibers and particles on the fracture conductivity

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Abstract. After temporary plugging and fracturing, some of the difficult-to-degrade temporary plugging agents (fibers and particles) in the fractures will affect the conductivity and ultimately affect the rate of oil production. However, the influence law and mechanism of the fibers and particles on the fracture conductivity are still unclear. In order to solve this problem, based on the FCS-842 fracture conductivity test system, the influence law and mechanism of fibers and particles on the fracture conductivity were investigated. The experimental results show that the larger particles support the fracture wall when particles are contained, resulting in higher conductivity. Further studies have found that high fibers content will lead to a significant decrease in the fracture conductivity under low closure pressure. However, high particle content means high fracture conductivity. The placement position of fibers and particles also affects the fracture conductivity. When the pressure is 10 MPa, the conductivity is maximum when the fibers and particles are placed at the fracture opening. Then, when the pressure increases, the conductivity drops sharply by about 88%. When the closure pressure is ≥ 20 MPa, the conductivity is the highest when the fibers and particles are placed at the fracture tip, followed by the middle of the fracture and the smallest at the fracture opening. After analysis, at the fracture opening, the high flow velocity forms a fiber "Barrier" in the fracture, which makes the conductivity decrease rapidly. In the middle of the fracture, the "Dot-net" structure composed of fibers and particles makes the fracture conductivity decrease, but the decrease amplitude and speed are small. At the fracture tip, the lower flow rate makes the fibers and particles form "Clusters", and the large flow channel between the clusters makes the fracture conductivity higher than the former two. When the fibers and particles are evenly laid, the fibers are easy to form clusters with the particles to block the flow channel, reducing the fracture conductivity.

1. Introduction

Hydraulic fracturing, as a technical means to effectively develop oil and gas, has been widely used [1-3]. Due to the complexity of reservoirs, conventional hydraulic fracturing measures show some shortcomings such as small reconstruction volume. Temporary plugging fracturing, as a new reservoir stimulation technology, generally blocks the original fractures with temporary plugging agent, and after pressure suppression, new artificial fractures are generated in other directions, thus realizing the propagation of fracture network [4-7]. However, the temporary plugging agents in the fracture after
temporary plugging will affect the hydraulic fracture conductivity, but the influence law is still unclear. Therefore, it is necessary to study the influence law and mechanism of temporary plugging agents on hydraulic fracture conductivity.

The degradation of temporary plugging agent is widely concerned, and incomplete degradation will pollute the formation and affect the conductivity of fractures. In recent years, the temporary plugging fibers and particles suitable for oilfield fracturing are most used. Particles temporary plugging agent was first proposed by Halliburton Company in 1972, and it is also the most widely used temporary plugging agent in the field at present [8]. The principle of the particles temporary plugging agent to form temporary plugging layer is to form bridge plugging at fractures or pore throats by particles aggregation [9]. Compared with particles temporary plugging agents, fibers temporary plugging agents have better plugging advantages [10-13]: it has good flexibility and remarkable plugging effect. Generally, it can be used for plugging large-size fractures and prevent the proppant from flowing back. Fiber temporary plugging agents are generally used in the construction of temporary plugging and turning acid fracturing [14-18]. In deep formations, high-concentration cross-linked gels are often used on site, which will cause undegraded residues to pollute the formation, damage the formation and reduce the fracture conductivity [19-21]. Martin et al. [22] used fiber temporary plugging agent to temporarily plug and fracture the carbonate reservoir. The fiber temporary plugging agent gradually degrades over time and has less pollution to the reservoir and reduces the impact on fracture conductivity. Kayumov et al. [23] found that the degradable fiber has very little degradation residue after hydraulic fracturing, and it does little damage to the reservoir. Based on the fracture conductivity test system, Liang et al. [24] found that the fibers reduced the fracture conductivity by 7.84% under the condition of formation temperature. However, the previous research only focuses on the effect of fibers and particles on fracture conductivity [25-28] and whether the degradation after plugging is complete [29-33]. However, the influence of fibers and particles that have not been degraded or incompletely degraded after temporary plugging on the fracture conductivity itself is rarely studied. In addition, the mechanism by which fibers and particles affect the fracture conductivity has not been discussed yet.

As an important parameter for evaluating the ability of filling proppant fractures to pass fluids, the fracture conductivity directly affects the production efficiency of oil and gas [34-36]. In recent years, many scholars have done a lot of research on the fracture conductivity. Based on 3D scanning and 3D engraving technology, Chen et al. [37] found that under low closure stress, the higher conductivity may be produced when the proppant concentration is lower than the "critical proppant concentration". Liu et al. [38] established a single-layer proppant fracture conductivity model. The results show that under the action of closing pressure, the fracture conductivity drops sharply when proppants with different particle sizes are embedded into rocks one after another. Xu et al. [39] analyzed the conductivity of tortuous fractures and found that lower proppant sphericity can reduce the fracture conductivity. Lei et al. [40] deduced the hydraulic fracturing model of proppant embedment compaction, which divided the conductivity curve into six stages. Based on the model results, proppants with larger elastic modulus and larger size used in the field are given. Based on the fracture conductivity test system, Wang et al. [41] found that proppant rupture, embedment and particle migration can reduce the conductivity of fractures. Based on the FCS-842 fracture conductivity test system, the results show that due to the fracture of the proppant, the fracture conductivity decreases with the increase of the effective closure stress [42]. Zhang et al. [43] found that the conductivity of the new self-generating solid proppant was higher than that of conventional proppants under the same conditions. Wang et al. [44] showed that gel breakers and their residues would have adverse effects on the fracture conductivity through experimental research.

Based on the above discussion, the influence law and mechanism of temporary plugging particles and fibers on the fracture conductivity are still unclear. In this paper, we have studied the influence law and mechanism of particles and fibers on the fracture conductivity through the conductivity test system. First, we studied the changes in the fracture conductivity when fibers and particles were laid alone and mixed. Second, we further investigated the role of the two in
affecting the conductivity by changing the ratio of fibers and particles. Third, the conductivity when fibers and particles are centrally laid at different locations is studied. Finally, based on the previous experimental results, we give the mechanism by which fibers and particles affect the fracture conductivity.

2. Experiment preparation

2.1. The fracture conductivity test

The fracture conductivity test follows Darcy’s law,

\[ K = \frac{99.998 \mu \cdot Q \cdot L}{A \cdot \Delta P} \]  

where the \( K \) is the permeability of sand-filled fracture (\( \mu \text{m}^2 \)), and the \( \mu \) is the fluid viscosity (\( \text{mPa}\cdot\text{s} \)) at test temperature. The \( Q \) is the fluid injection speed (\( \text{cm}^3/\text{s} \)), and the \( L \) is the length between pressure taps (cm). The \( A \) represents the flow channel area (\( \text{cm}^2 \)), and the \( \Delta P \) is the pressure difference (the upstream pressure minus downstream pressure, kPa). In addition, the 99.998 is the coefficient.

When the sand-filled layer is the rectangle, the \( A \) is given:

\[ A = W \cdot W_f \]  

where the \( W \) is the width of the proppant filled in the diversion chamber (cm), and the \( W_f \) is the thickness of the proppant filled in the diversion chamber (cm).

so the permeability of sand-filled fracture is as follows:

\[ K = \frac{99.998 \mu \cdot Q \cdot L}{W \cdot \Delta P \cdot W_f} \]  

The fracture conductivity is defined as the product of permeability and fracture width, from which it can be concluded that the conductivity of sand-filled fracture is:

\[ K \cdot W_f = \frac{99.998 \mu \cdot Q \cdot L}{W \cdot \Delta P} \]  

where the value of the \( W \) is 3.81 cm, and the value of the \( L \) is 12.70 cm. After the unit conversion, the conductivity of sand-filled fracture in the experiment is given:

\[ K \cdot W_f = \frac{5.555 \mu \cdot Q}{\Delta P} \]  

where the \( K \cdot W_f \) is the conductivity (\( \mu \text{m}^2\cdot\text{cm} \)), and the \( \mu \) is the fluid viscosity (\( \text{mPa}\cdot\text{s} \)) at test temperature. The \( Q \) is the fluid injection speed (\( \text{cm}^3/\text{min} \)), and the \( \Delta P \) is the pressure difference (the upstream pressure minus downstream pressure, kPa).

2.2. The experimental device

Figure 1 shows the testing cell for the fracture conductivity, which includes a diversion chamber, fluid inlet and outlet, two metal plates (simulating fracture surface), top and bottom fittings (providing closure pressure), and pressure taps. Meanwhile, the cell size is shown in Figure 1. In the experiment, the temporary plugging agent and quartz sand were mixed evenly according to a certain proportion, and filled between two metal plates in the diversion chamber, and then the closure pressure was generated by the top and bottom fittings. The sand concentration of this experiment is 8 kg/m\(^2\); Distilled water is used as medium fluid for displacement, and the displacement flow rate is 2.5 ml/min. Finally, the assembled test unit is put into the hydraulic press of FCS-842 fracture conductivity test system (Core-Lab, USA) (Figure 2) to control the closure pressure. Seven pressure points (10 MPa-70
MPa) were selected for each experiment, and each pressure point lasted 15 min. The test unit and other devices are connected in the connection mode shown in Figure 2 (Right).

![Diagram showing the test unit and other devices connected in a specific mode.](image)

**Figure 1.** The testing cell for the fracture conductivity.

**Figure 2.** FCS-842 fracture conductivity test system.

2.3. **The experimental materials**
The fibers and particles used in the experiment are temporary plugging agents developed independently and widely used in oil fields (Zhou et al., 2017). And fibers and particles are used alone or in combination, which is used to study the influence on the fracture conductivity. The fibers (Figure 3(a)) and particles (Figure 3(b)) used in this experiment are copolymers of lactic acid and glycolic acid. Among them, the average length of the fiber is 6 mm, and the average diameter is 10-13 μm. The average particles size is 3 mm, and the particles density is 1.0-1.1 g·cm$^{-3}$. The size of the quartz sand (Figure 3(c)) is 40/70 mesh, and the density is 2.60-2.70 g·cm$^{-3}$. 
3. Results and Discussions

In the paper, we focused on the analysis of the influence of the mixing, laying position and content of temporary plugging agents on the fracture conductivity. And the mechanism of temporary plugging agents affecting the fracture conductivity is also studied.

3.1. The influence of different temporary plugging agents (fibers or particles) on the fracture conductivity

Figure 4 shows the distribution of different temporary plugging agents in the diversion chamber, in which proppant-quartz sand (Q) is laid. Figure 4 (a) contains no temporary plugging agent, Figure 4 (b) contains only fibers (F), Figure 4 (c) contains only particles (P), and Figure 4 (d) contains both particles and fibers (Note that the temporary plugging agent is uniformly laid in the proppant).

Figure 3. Fibers, particles and quartz sand used in the experiments.

Figure 4. Distribution of different temporary plugging agents in diversion chamber.
Figure 5 (a) shows the curve of the fracture conductivity changing with closure pressure under the combinations of temporary plugging agents. The results show that the conductivity shows a downward trend under the combinations of temporary plugging agents with the increase of closure pressure. Under various closure pressures, the fracture conductivity is the highest when only 1% particles are contained, followed by those containing 0.5% fibers and 1% particles, and the conductivity of only 0.5% fibers is the lowest. Liang et al. (2018) found that fiber residues can reduce the fracture conductivity by 7.84%. Our results are consistent with their results. However, we considered the influence of the combination of the particles and fibers, which is more general. Our results illustrate that particles can significantly increase the fracture conductivity, while fibers reduce the fracture conductivity. After the experiments, the quartz sand was screened and analyzed, and the mass ratio of the quartz sand with different particle sizes was obtained (Figure 5 (b)). When the particles size is in the range of 40/70 mesh, the proportion of the quartz sand (Q) without the particles (0.5% F, 100% Q) is relatively small, while the proportion of the quartz sand with particles (1% P, 0.5% F+1% P) is relatively large. When the particles size is less than 70 mesh, the proportion of the quartz sand without particles (0.5% F, 100% Q) is higher than that with particles (1% P, 0.5% F+1% P). This indicates that more quartz sand will be crushed due to extrusion when there are no particles, and the fractures will be closed to a greater extent, which results in a decrease in the fracture conductivity. When the particles are contained, most quartz sand particles cannot be broken by extrusion because the larger particle size supports the fracture wall, the conductivity is higher. For those containing fibers, because the fibers will block part of the flow channels, the conductivity is relatively low. Figure 6 shows the change curve of the conductivity with time. It can be found that the conductivity shows a downward trend with the increase of time. Among them, the conductivity of 1% P is always greater than the conductivity of all fibers. Due to the support of the particles, the conductivity of 1% P eventually remains at a high level.

![Figure 5](image1.png)

**Figure 5.** The curves of the fracture conductivity (a) and particle size distribution (b) under the combination of temporary plugging agents.

![Figure 6](image2.png)

**Figure 6.** Change curve of conductivity with time
3.2. The influence of the fiber and particle ratio on the fracture conductivity
In order to further clarify the influence of temporary plugging particles and fibers on the fracture conductivity, according to the construction experience of mass concentration of temporary plugging agents on site (Yang, et al., 2019), we considered the combination of fibers and particles with gradient concentration of 0.5% respectively, including 0.5% F+1.5% P, 1% F+1% P and 1.5% F+0.5% P. In order to reduce the influence of uneven distribution of fibers and particles caused by mixed laying on the experimental results, the fibers and particles were concentrated in the middle of fractures (Same as section 3.3). Figure 7 shows the curve of the fracture conductivity changing with closure pressure under various combination conditions. When containing 1.5% F and 0.5% P, the fracture conductivity drops rapidly in the closure pressure range of 10 MPa-30 MPa, with a drop range of 83%. This indicates that particles and fibers under this combined condition can greatly reduce the fracture conductivity. When 1% F and 1% P are contained, the decreasing amplitude of the fracture conductivity is the same as that of the former in the closure pressure range of 10 MPa-30 MPa, but the decreasing speed is reduced. When the fibers content is 0.5%, the fracture conductivity decreases by about 71% in the closure pressure range of 10 MPa-30 MPa, and at the same time, the decreasing speed becomes slower. When the closure pressure is greater than 60 MPa, the fracture conductivity gradually tends to zero.

By comparing the fracture conductivity under different fibers and particles combinations, we find that high fibers content can lead to a significant decrease in fracture conductivity under low closure pressure. And the higher the fiber content, the faster the decrease in conductivity. However, a high particle content means a high fracture conductivity, and at the same time, the decreasing amplitude and speed of the fracture conductivity are reduced, which is due to the fact that the temporary plugging particles can form a larger flow channel inside the fracture.

3.3. The influence of the fiber and particle placement position on the fracture conductivity
In order to investigate the influence of the placement position of temporary plugging agents in fractures on the conductivity, we have considered the variation law of the fracture conductivity when the temporary plugging agents are in the fracture opening, the middle of fracture and the fracture tip respectively.

Figure 8 shows the conductivity of temporary plugging particles and fibers at different placement positions. It can be found that the conductivity is the largest when the temporary plugging agents are placed in the fracture opening under 10 MPa, which is almost twice the conductivity of the temporary plugging agents when they are placed in the middle of fracture. When the closure pressure is 20 MPa, the conductivity of the temporary plugging agents when they are placed in the fracture opening drops drastically, down by about 88%. When the fracture closure pressure is ≥ 20 MPa, the conductivity of the temporary plugging agents placed at the fracture tip is the largest, followed by the conductivity of
the temporary plugging agents placed in the middle of fracture, and the conductivity of the temporary plugging agent placed at the fracture opening is the smallest. In order to explain the law of the fracture conductivity, we analyzed the distribution of temporary plugging particles and fibers after the experiments (Figure 9). The results show that the fibers are carried to the junction of temporary plugging agents and quartz sands due to the high flow velocity in the fracture opening, and a "barrier" similar to the dam is formed, which greatly reduces the conductivity of the fracture (Figure 9 (a)). As the fluid flow speed slows down in the middle of fracture, the fibers and particles form a "dot-net" like interweaving body, which reduces the fracture conductivity (Figure 9 (b)). However, compared with the fracture opening, there are channels for fluid flow in this "dot-net" structure, which leads to the improvement of the conductivity. At the fracture tip, the flow velocity is slower, which causes the fibers to form "clusters" (Figure 9 (c)). Therefore, a larger flow channel is generated at the fracture tip, and the conductivity is further increased.

![Figure 8](image1)

**Figure 8.** The fracture conductivity under different placement positions (Left, placing position, red rectangle. Right, the conductivity).

![Figure 9](image2)

**Figure 9.** The distribution of the particles and fibers at different placement positions after the experiment.

3.4. **Mechanisms affecting the fracture conductivity**

Based on the previous experimental results, it can be seen that the fibers and particles in different placement modes have different influences on the fracture conductivity. In this paper, we consider two cases of centralized placement and uniform placement, and give the mechanism that the fibers and particles affect the fracture conductivity in both cases.
Figure 10 shows the influence of fibers and particles on the fracture conductivity under the condition of centralized placement. Figure 10 (a) and (b) show the changes of fibers and particles at the fracture opening before and after the experiment. Figure 10 (c) and (d) show the changes of fibers and particles in the middle of the fracture before and after the experiment. Figure 10 (e) and (f) show the changes of fibers and particles at the fracture tip before and after the experiment. In this paper, we refer to the research ideas of Yang et al. (2019) on the mechanism of temporary plugging of fractures with temporary plugging agents, and combine the changes of the particles and fibers distribution before and after the experiments, and finally give the mechanism that fibers and particles affect the fractures conductivity.

The fluid flows into the fracture from the fracture opening. Due to the rapid flow rate, the fluid carries the fibers to the interface between the quartz sand and the placement section, and gradually accumulates at the interface to form "Barrier", as shown in Figure 10 (a) and (b). This "Barrier" blocks fluid flow channels and greatly reduces the fracture conductivity. In the middle of fracture, with the gradual decrease of the flow velocity, after being dispersed by the fluid, the fibers and temporary plugging particles form a "dot-net" structure (Figure 10 (c) and (d)), which hinders the flow of the fluid. However, there are some small flow channels in the structure, which leads to the decrease of the conductivity in this case, but the decrease is smaller and the velocity is lower. At the fracture tip, the smaller flow rate makes the fibers form "Clusters" around the particles (Figure 10 (e) and (f)), and the larger gap between the clusters forms a fluid flow channel. Therefore, the fracture conductivity in this case is relatively large. Based on the above analysis, the influence mechanism of concentrated placement of the fibers and particles on the fracture conductivity can be summarized as follows:

1. At the fracture opening, the high flow velocity forms a fiber "Barrier" in the fracture, which makes the conductivity decrease rapidly.
2. In the middle of the fracture, the "Dot-net" structure composed of fibers and particles makes the fracture conductivity decrease, but the decrease amplitude and speed are small.
3. At the fracture tip, the lower flow rate makes the fibers and particles form "Clusters", and the large flow channels between the clusters makes the fracture conductivity higher than the former two.

Figure 10. Schematic diagram of influence of fibers and particles centralized placement on the fracture conductivity (top view).

Figure 11 shows the schematic diagram of influence of fibers and particles uniformly placement on the fracture conductivity. After entering the fracture, the fluid carries the fibers forward, and many fibers surround the particles when they meet the particles in the quartz sand, forming clusters to block part of the flow channels. However, the position change of particles is small. Therefore, it can be found that the fibers and particles are carried by the fluid to form a cluster when the fibers and
particles are evenly laid, which blocks part of the flow channels, resulting in a decrease in the fracture conductivity.

**Figure 11.** Schematic diagram of influence of fibers and particles uniformly placement on the fracture conductivity (top view).

### 4. Conclusion

Based on the FCS-842 fracture conductivity test system, the influence law and mechanism of fibers and particles on the fracture conductivity were investigated. The following conclusions are drawn through the experiments:

1. Larger temporary plugging particles support the fracture wall, forming a large flow channel, which leads to higher conductivity. The fibers will block part of the flow channels, so the conductivity is relatively low.

2. Furthermore, it is found that high fiber content will lead to a significant decrease in fracture conductivity under low closure pressure (10 Mpa-30 Mpa). However, a high particle content means the high conductivity, and at the same time, the magnitude and speed of the decline in the conductivity are reduced.

3. The placement position is one of the factors that affect the fractures conductivity. When the pressure is 10 MPa, the conductivity is maximum when the fibers and particles are placed at the fracture opening. Then, when the pressure increases, the conductivity drops sharply by about 88%. When the closure pressure is $\geq$ 20 MPa, the conductivity is the highest when the fibers and particles are placed at the fracture tip, followed by the middle of the fracture and the smallest at the fracture opening.

4. The high flow velocity in the fracture opening caused the fiber to form a "Barrier" similar to a dam at the interface between the temporary plugging agents and the quartz sand, which greatly reduced the fracture conductivity. As the flow rate slows down, the fibers and particles form a "Dot-net" structure in the middle of the fracture, thereby reducing the conductivity. However, compared with fracture opening, there are channels for fluid flow in this "dot-net" structure, which leads to an increase in the conductivity. At the fracture tip, the slower flow rate causes the fibers to form "Clusters", which creates larger channels and further improves the conductivity. When the fibers and particles are evenly laid, the fibers are wound around the particles to form clusters with the particles, thus reducing the flow channels and reducing the diversion capacity.

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