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Experimental Investigation of Fracture Conductivity in Shales Considering Proppant Embedment and Crushing

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ABSTRACT

Unconventional oil and gas resources, such as shale oil and gas, are gradually attracting great attention from all of the world. Horizontal drilling and large-scale hydraulic fracturing technology are used to efficiently extract oil from shale formation. A high long-term conductivity is essential for hydraulic fracturing, so accurate evaluation of propped fracture conductivity is of great significance for the development of shale reservoirs. In this paper, FCMS-V fracture conductivity system, scanning electron microscope and sieve analysis were used to study the influence of various factors on fracture conductivity, proppant crushing and embedment under reservoir conditions of the DG shale formation in Songliao basin. A visual study of proppant embedment into the shale rock was carried out. The effects of granule size, granulometric composition, concentration of proppants and closure pressure on fracture conductivity were revealed. It was found that due to the embedment of proppants, the long-term conductivity decreases by 10.2%. After exposure to a closure pressure of 30 MPa, the degree of crushing of the 30/50, 40/70 and 70/140 mesh proppants are 56.9, 38.8 and 26.7%. The findings from this experimental study could help hydraulic fracturing design for long term production of shale reservoirs.

Keywords: shale oil, fracture conductivity, proppant embedment, proppant crushing

1. INTRODUCTION

The decrease in conventional oil and gas reserves combined with the continuous increase in crude oil consumption have led countries to pay more attention to unconventional oil and gas resources [[1], [2], [3], [4]]. In recent years, China has discovered huge shale oil reserves [5, 6], which has brought hope for reducing its growing dependence on oil imports.

Shale oil reservoirs usually have low porosity and permeability, and oil mainly exists in the micro or even nano pores. Horizontal drilling and large-scale hydraulic fracturing techniques are used to effectively extract shale oil [7]. After hydraulic fracturing, the fractures are filled with proppants to maintain a long-term conductivity under closure pressure. However, the fracture conductivity of shales rapidly decreases within a few months after hydraulic fracturing [8]. This leads to a rapid production decline, dropping to 90% in the second year, which is a typical trend in shale oil production. Therefore, ensuring an effective support of proppants and high long-term fracture conductivity is the key to improving shale oil and gas well performance.

There are many factors that can reduce fracture conductivity, such as increased fracture closure pressure [[9], [10], [11]], proppant embedment [12, 13], proppant crushing [14], fracturing fluid residual blockage [15], particle migration [14] and proppant diagenesis [16], etc. These effects on fracture conductivity in shale reservoirs are different from those of conventional reservoirs due to high clay content in shales.

Experimental study is one of the most effective methods for evaluating the conductivity of hydraulic fracturing fractures. This study quantitatively evaluated the effect of proppant size, combined proppant size composition, proppant concentration, closure pressure, embedment and crushing on fracture conductivity by using the FCMS-V fracture conductivity measurement system, automatic emission scanning electron microscope, and sieve analysis method. The experimental results are of great significance for optimizing hydraulic fracturing technology in shale oil reservoirs.

2. EXPERIMENTAL STUDIES

2.1 Experimental equipment and procedures

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

In this study, fracture conductivity experiment procedure refers to two standards: ISO 13503-5 [17] and NB/T14023-2017 [18]. It is recommended to install a conductive unit between two pieces of shale core samples. The ISO 13503-2 [19] and SY 17125-2019 [20] standards are used to measure the percentage of different sizes of proppants.

The FCMS-V fracture conductivity system (Fig. 1) allows experiments to be conducted under simulated formation conditions at high pressure (up to 150 MPa) and temperature (up to 200 ℃). During the experiment, a computer system (including data collection, processing, and control system) automatically measured fracture width (accuracy —0.001 mm), conductivity cell temperature and working fluid temperature, flow rate, and pressure difference (accuracy —0.01 KPa).

Fig. 1 FCMS-V fracture conductivity measurement system

Table 1. Detailed design of fracture conductivity experiment

NO.	Research factors	Patten of experiment samples	Proppant particle size	Proppant concentration(g/cm^2)	Particle size composition	Closure pressure (MPa)
1	Proppant size	Shale platens	30/50	0.5	—	30
2		Shale platens	40/70	0.5	—	30
3		Shale platens	70/140	0.5	—	30
4	Proppant size composition	Shale platens	30/50:40/70:70/140	0.5	1:1:1	30
5		Shale platens	30/50:40/70:70/140	0.5	1:4:5	30
6		Shale platens	30/50:40/70:70/140	0.5	1:2:7	30
7	Proppant concentration	Shale platens	30/50:40/70:70/140	0.25	1:2:7	30
8		Shale platens	30/50:40/70:70/140	1	1:2:7	30
9	Closure stress	Shale platens	30/50:40/70:70/140	0.5	1:2:7	20
10		Shale platens	30/50:40/70:70/140	0.5	1:2:7	40
11	Proppant embedment	Shale platens	30/50:40/70:70/140	0.5	1:2:7	30
		Steel platens				

Quartz sand is widely used in hydraulic fracturing in China, so 30/50, 40/70, and 70/140 sands were used as proppants in this study. The shale core samples were taken from DG shale formation in Songliao basin. 2% potassium chloride aqueous solution is recommended as the working liquid according to the above standards.

In this work, the experiment was conducted at a temperature of 90 °C and the closure pressures were set to 20, 30, and 40 MPa. The effect of various factors on long-term conductivity of fractures were studied using the FCMS-V system mentioned above. Automatic emission scanning electron microscopy was used to visualize proppant embedment into shale cores. The proppant crushing rate was measured by sieving method. The detailed experimental design is shown in Table 1.

2.2 Results of conductivity experiment

This part discusses the experimental results of the effects of proppant size and concentration, proppant size composition, and fracture closure pressure on the long-term conductivity of fracture.

In order to determine the stable time of conductivity during the experimental process, this paper introduces the concept of conductivity change rate, which is defined as follows:

$$T_i = \frac{C_i - C_{i-1}}{C_i} \text{..................................} (1)$$

In Eq.1, T_i is the current conductivity change rate, C_i is the current fracture conductivity, and C_{i-1} is the fracture conductivity at previous measurement time.

The duration of conductivity experiment is 50 hours. If the conductivity change rate within 2 hours is less than 2%, it is considered that the conductivity is stable.

2.2.1. Effect of proppant size

Figure 2 shows how the fracture conductivity changes with time for different proppant size with a proppant concentration of 5kg/m^2 at a temperature of 90 °C under closure pressure of 30MPa. The initial conductivity values of 30/50, 40/70, and 70/140 proppant test were 12.72, 4.68, and 1.13 d-cm, and after 50 hours the values decreased by 61.5%, 47.9%, and 36.3%, which indicates the larger the proppant size, the higher initial conductivity value and the greater decrease in conductivity. It is also noticed that the smaller the size, the faster the conductivity stabilizes. After 22 hours, 14 hours, and 8 hours running, the fracture conductivity of 30/50, 40/70, and 70/140 proppant remained stable. From the experiment results, it can be seen that 30/50 proppant has better conductivity than 40/70 and 70/140 proppant.

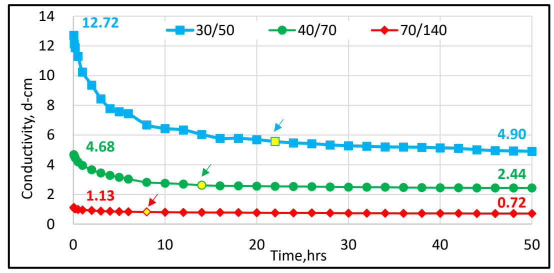

Fig. 2 Effect of proppant size on fracture conduc*tivity*

2.2.2. Effect of proppant size composition

Figure 3 shows how the fracture conductivity changes with time for different proppant size composition with a proppant concentration of 5kg/m^2 at a temperature of 90 °C under closure pressure of 30MPa. The mass ratios of combined 30/50, 40/70 and 70/140 proppant were 1:1:1, 1:4:5 and 1:2:7. The initial conductivity values were 5.93, 3.29, and 2.52 d-cm, and after 50 hours the values decreased by 42.8%, 38.6% and 33.7%. Results indicate that large size proppant has a significant impact on conductivity. The higher the mass ratio of small particles, the lower the conductivity value, and the faster the conductivity stabilizes.

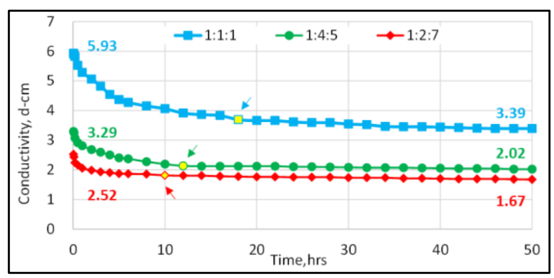

Fig. 3 Effect of proppant size composition on fracture conduc*tivity*

2.2.3. Effect of proppant concentration

This section discusses the effect of proppant concentration (2.5, 5, and 10 kg/m^2) on fracture conductivity with a combined proppant mass ratio of 1:2:7 under closure pressure of 30 MPa. Field practice has proven that mass ratio 1:2:7 is suitable for hydraulic fracturing of DG shale formations. As shown in Fig. 4, proppant concentration has a significant impact on conductivity, as it directly determines the width of fracture. At concentrations of 2.5, 5, and 10 kg/m^2, the initial conductivities were 1.42, 2.52 and 4.61 d-cm, and after 50 hours the values decreased by 33.8%, 33.7% and 32.1%. Results indicate that the lower the proppant concentration, the greater the decrease in conductivity and the faster it stabilizes.

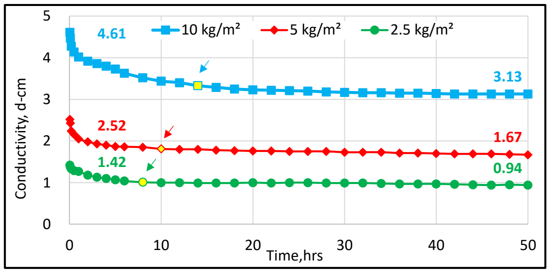

Fig. 4 Effect of proppant *concentration* on fracture conductivity

2.2.4. Effect of closure pressure

Figure 5 shows changes in conductivity over time under closure pressures of 20, 30, and 40 MPa at a proppant concentration of 5 kg/m^2, with a combined proppant mass ratio of 1:2:7. In the process of oil well production, with the extraction of formation fluids, the well pressure decreases, resulting in an increase in closure pressure on proppants. As shown in Fig. 5, as the closure pressure increased from 20 MPa to 30 and 40 MPa, the long-term conductivity values decreased by 21.6% and 35.2%. Under high closure pressure, proppants deformed and part of them were broken. Results indicate that the higher the closure pressure, the lower the initial and long-term conductivity value, and the faster the conductivity stabilizes.

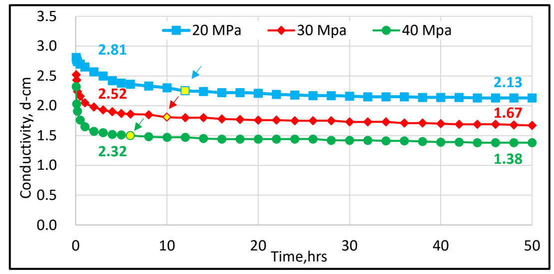

Fig. 5 Effect of closure pressure on fracture conductivity

2.3 Visualization of proppant embedding

Automatic emission scanning electron microscopy was used to visualize proppant embedment into shale cores. Figure 6 is the embedment image of proppants. It can be clearly seen that the larger the particle size, the more indentations there are, and the larger the particle size, the deeper the indentations.

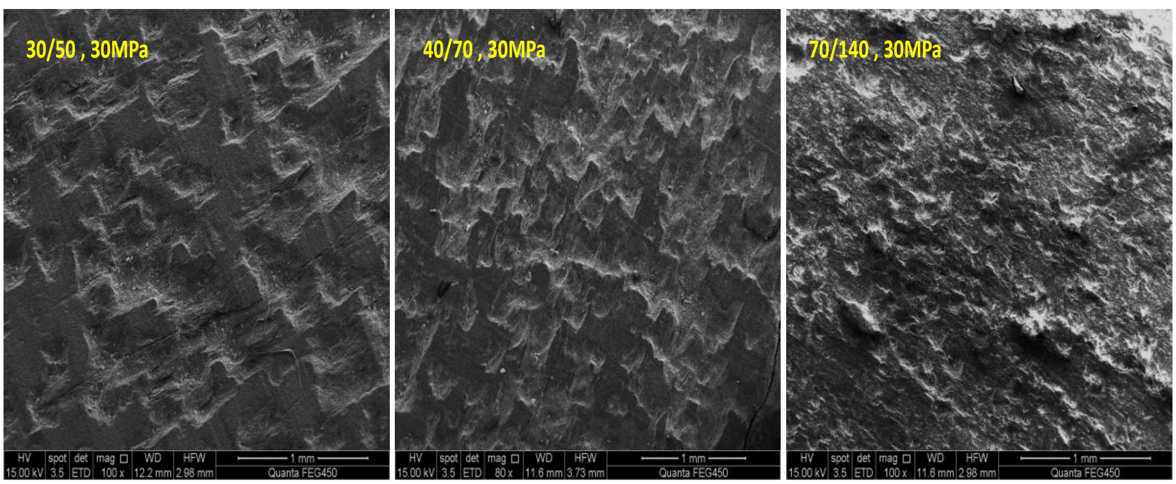

Fig.6 Images of proppant embedment.

Figure 7 shows experimental results of steel platens (11th experiment) and shale platens (6th experiment). The initial conductivity value with and without proppant embedment were 2.52 and 2.49 d-cm, and after 50 hours the values decreased to 1.67 and 1.86 d-cm, which indicates 10.2% conductivity damage due to proppant embedment. Compared with the initial values, the final conductivity decreased by 33.7% and 25.3% respectively, and stabilized within 10 and 8 hours. This indicates that the indentation gradually increases over time.

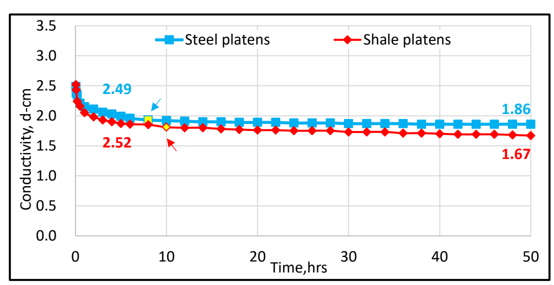

Fig. 7 Effect of proppant embedment on fracture conductivity

2.4 Analysis of proppant crushing

This part discusses the effect of proppant crushing on fracture conductivity and analyzes the crushing degree of proppants under a closure pressure of 30 MPa. In experimental study of long-term fracture conductivity, the degree of proppant crushing is measured by the mass ratio of crushed particles.

Fig. 8 shows the mass ratio analysis results of different sizes particles before and after loading closure pressure (30 MPa) at a proppant concentration of 5 kg/m^2, with a combined proppant mass ratio of 1:2:7 (6th experiment). The initial average particle sizes of the 30/50, 40/70, and 70/140 mesh were 415.3, 291.0, and 156.1 micrometers, and after experiments, they were 292.7, 230.1, and 131.0 micrometers, which indicates 29.5%, 20.9%, and 16.1% decrease. The larger particles underwent greater changes.

During experiments, large particles were crushed into small particles, resulting in a decrease in the mass ratio, while the mass ratio of small particles increased. This causes a tighter particle package between platens and reduces fracture conductivity. After long-term conductivity experiment, the crushing rates of 30/50, 40/70, and 70/140 proppant were 56.9%, 38.8%, and 26.7%. In different experiments of this study, proppant embedment and crushing can lead to significant damage to long-term conductivity, for this case -33.7%.

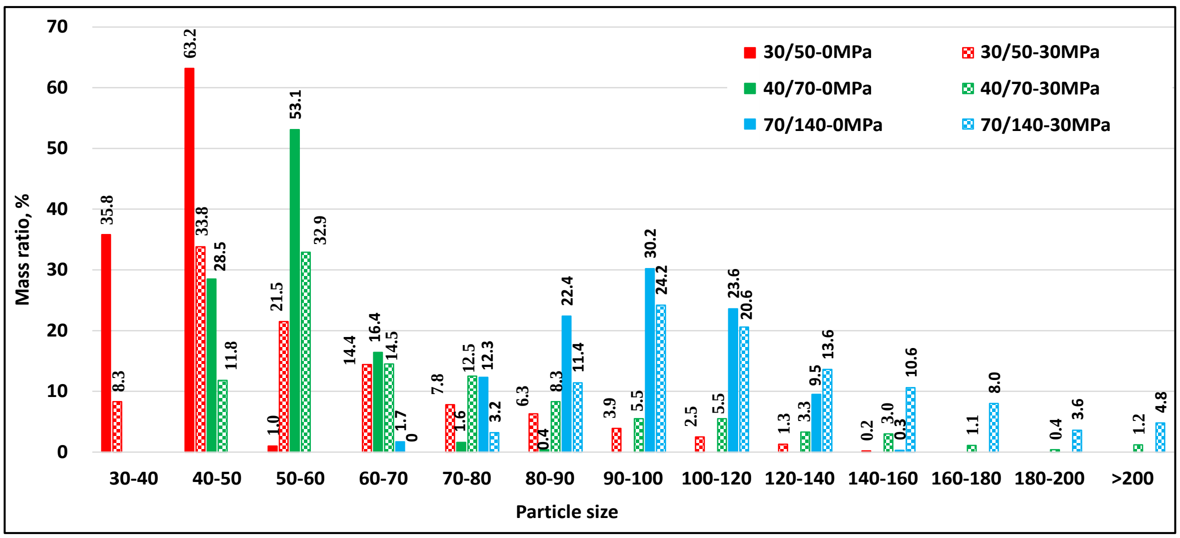

Fig. 8 Results of sieve analysis before and after long-term conductivity experiment

2.5 Conclusions

The experimental results are helpful for evaluating the effects of different factors on long-term fracture conductivity, proppant embedment and crushing of DG shale formation in Songliao basin. The following conclusions are made based on the experimental results of this study:

1. There is a positive correlation between fracture conductivity and particle size and concentration.
2. Large size particle has a significant impact on conductivity. The higher the mass ratio of small particles, the lower the conductivity value, and the faster the conductivity stabilizes.
3. Under high closure pressure, proppants deformed and part of them were broken, resulting in a decrease in conductivity. When the closure pressure increased from 20 MPa to 30 and 40 MPa, the long-term conductivity values decreased by 21.6% and 35.2%. Therefore, it is recommended to extract shale oil while maintaining bottomhole pressure to reduce the closure pressure on proppant package.
4. Due to proppant embedment, the long-term fracture conductivity decreased by 10.2%. Embedment indentation gradually increases over time.
5. Proppant crushing causes a tighter particle package between platens and reduces fracture conductivity. Large particle has higher crushing rate.
6. In different experiments of this study, proppant embedment and crushing can lead to significant damage to long-term conductivity, in the 6th experiment — 33.7%.

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