Experimental study on settlement law of multi-particle compound temporary plugging material in rough fracture

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Abstract. To study the migration and settlement law of temporary plugging particle in fractures, a set of fracture visualization device with controllable pumping rate was built. Based on the experimental device, the influence of the parameters such as pumping rate, particle size combination and adding sequence on the sedimentation and accumulation of temporary plugging particle was studied respectively. The experimental results show that the amount of particle deposition in the fracture is the largest when the pumping rate is 0.04 m\textsuperscript{3}\text{•min}\textsuperscript{-1}; Under different particle size combinations, 3 mm particles settle earlier than 1 mm particles and the volume of the accumulation is proportional to the proportion of 3 mm particles. The effect of the sequence of addition on the morphology of the particle accumulation is mainly reflected in the layering of the accumulation. When the 3 mm particles are added first and then the 1 mm particles are added, the accumulation volume is larger and the particles settle more. In summary, when a combination of 0.04 m\textsuperscript{3}\text{•min}\textsuperscript{-1} rate and 3 mm: 1 mm=4:2 particle size is selected, and 3 mm is added first, and then 1 mm particles are added, the temporary plugging particle has a larger volume of sedimentation in the fracture.

1. Introduction

Tight reservoirs generally have the characteristics of poor physical properties and low production, which require fracturing for production [1-4]. Temporary plugging particles can promote fracture turning, forming a complex network of fractures and achieve the purpose of Stimulated reservoir volume(SRV) [5]. The main function of temporary plugging particles is to reduce the permeability of the formation, change the flow direction of the fluid, create new lateral fractures, and extract as much remaining oil as possible [6]. During the pumping process, temporary plugging particles settle and accumulate in the fractures, but the law is still unclear. The properties of proppant and temporary plugging particles are different, but their migration and settlement laws in fractures are similar. This article refers to previous scholars' research results on proppants.

Scholars at home and abroad mainly use physical model experiments to study the migration and settlement laws of proppant in fractures. Wen Qingzhi and Li Liang [7] [8] studied the migration and settlement laws of proppant in fractures by designing fracture simulation experimental devices. They found that the main factor affecting proppant horizontal movement and settlement speed is proppant diameter, proppant density and fracturing fluid viscosity. Gao Jinjian [9] found that the complexity of the fracture network in the device and the pumping rate also affect the migration of proppant. Wen
Qingzh [10] further derived the relationship between proppant migration distance and fracture network structure on the basis of the former, among which the proppant migration distance in the long straight fracture is the farthest. Liang Ying [11] believed that the pumping rate is directly proportional to the proppant horizontal migration speed and inversely proportional to the vertical settlement speed. Pan Linhua [12] also believed that the pumping rate not only affects the migration and settlement speed of the proppant, but also affects the accumulation morphology of the proppant. Di Wei [13] combined numerical simulation and physical experiments to consider the relationship between the proppant volume fraction and the equilibrium height of the proppant bank, and proved that the proppant volume fraction has a positive effect on the equilibrium height of the bank. Zhang Kuangsheng [14] and others designed an experimental program of proppant combinations with different particle sizes, and found that the proppant migration distances under different particle size combinations are significantly different.

Some scholars have also studied the migration and settlement laws of proppant in fractures through numerical simulation and theoretical calculation. Wen Qingzh et al. established a mathematical model of proppant settlement, and the study showed that pumping displacement and fracturing fluid viscosity are the main factors affecting proppant settlement. Liu Chunting [15] further studied the influence of fracturing fluid viscosity, proppant density and pumping rate on the proppant migration and sedimentation morphology. Sun Haicheng [16] and Zhang Guodong [17] found that the settlement of proppant is mainly affected by the complexity of the fracture network, and the rough fracture wall can reduce the settlement velocity of temporary plugging particles. Xu Jiaxiang [18] found that the proppant will not move uniformly when migrating in tortuous micro-fractures, and will accumulate at the end of the fracture under the condition of high concentration of proppant.

Combined with previous studies on the migration and settlement laws of proppant in fractures, we independently developed a visualized rough fracture temporary plugging particle sedimentation accumulation system device. The migration and settlement laws of temporary plugging particles under the conditions of different pumping rate, particle size combination and adding sequence are studied, which provides a reference for on-site temporary plugging and fracturing construction.

2. Experiment preparation

2.1. Experiment law
Use an electric submersible pump to inject the proppant-laden fluid into the visualized rough fractures, and wait for the proppant-laden fluid to completely fill the fractures and stabilize. Then add the weighed temporary blocking particles, and use a stirrer to make the particles evenly dispersed in the proppant-laden fluid. The temporarily plugging particles settle and accumulate in the rough fractures under the action of their own gravity. The sedimentation velocity and accumulation form of the temporary plugging particles will vary with different experimental schemes. In the experiment, the real-time migration and settlement of temporary plugging particles was observed through visual fractures, and the migration and settlement laws of temporary plugging particles in rough fractures were obtained.

Configure a certain amount of proppant-laden fluid and place it in the storage tank; select the pumping rate, pump the proppant-laden fluid into the entire system, and circulate for a period of time; weigh a certain amount of temporary plugging particles and pour it into the storage tank, and stir well; Temporary plugging particles are pumped into the rough fracture device, and the proppant-laden fluid carries temporary plugging particles to migrate in the fractures; adjust various parameters to observe the migration and sedimentation process of temporary plugging particles in the fracture; record the migration status and particles of temporary plugging particles Stacked geometric forms.

2.2. Experiment device
The visual fracture is composed of three pairs of rough fracture panels (from left to right: F1, F2 and F3) (Figure 1). The width of the fracture formed in the middle of each pair of rough fracture panels is
between 8 mm and 12 mm. In the upper left corner of F1 and the upper right corner of F3 are the liquid outlet and inlet ends of the device, respectively.

![Visual rough fracture device](image)

**Figure 1.** Visual rough fracture device.

The visual fracture device consists of an electric submersible pump, a liquid storage tank, a visual fracture and a frequency converter, as shown in Figure 2. The maximum capacity of the liquid storage tank is 0.07 m\(^3\), the pumping rate of the electric submersible pump is adjustable, and the maximum pumping rate is 0.05 m\(^3\) min\(^{-1}\).

![Simulation device for temporary plugging particle sedimentation and accumulation in rough fractures](image)

**Figure 2.** Simulation device for temporary plugging particle sedimentation and accumulation in rough fractures.

This paper uses simplified schematic diagrams to represent the accumulation of particles in the device in order to better describe the migration and settlement laws of temporary plugging particles in the device and the accumulation of temporary plugging particles in rough fractures.

The flow trajectory of the fluid in the visualization device is shown in Figure 3 (black solid line), and the red arrow indicates the migration trajectory of the temporary plugging particles after entering the device.

![Flow trajectory of temporary plugging particles in rough fracture simulation device](image)

**Figure 3.** Flow trajectory of temporary plugging particles in rough fracture simulation device.
2.3. Experiment materials
Temporary plugging particles of different sizes have different sedimentation and accumulation rules in rough fractures. This paper uses particles of 3 mm and 1 mm in size (Figure 4). The density of temporary plugging particles of different particle diameters is between 1.0-1.1 g·cm$^{-3}$, and the proppant-laden fluid is clean water.

Figure 4. Particles of 3 mm (left) and 1 mm (right).

3. Result and Discussion
The experiment mainly analyzed the influence of pumping rate, particle size combination and adding sequence on the migration and settlement of temporary plugging particles in rough fractures. The selected particle concentration in this experiment is 1%. By measuring the volume, morphology and distribution characteristics of particle accumulations in fractures, the migration and settlement laws of temporary plugged particles in rough fractures are characterized.

3.1. Effect of pumping rate
Pumping rate is one of the main factors that affect the migration and settlement of temporary plugged particles in rough fractures. Adjust the pumping rate and observe the migration and settlement changes of temporary plugging particles. The experiment scheme is shown in Table 1.

| Particle size (mm) | Pumping rate (m³·min$^{-1}$) |
|-------------------|-----------------------------|
| 3                 | 0.035                       |
|                   | 0.040                       |
|                   | 0.050                       |

It can be found that the temporary plugging particles accumulate in the form of sand banks in the rough fractures, and the accumulation of particles in the fracture F1 is obviously more than that in other locations. And as the pumping rate increases, the particle accumulation in the rough fractures moves towards the left boundary of F1-the export; the smaller the pumping rate, the larger the volume of the particle accumulation at F2. When the pumping rate is 0.05 m³·min$^{-1}$, the accumulation at F2 almost disappears. However, based on all the results, the volume of the accumulation of temporary plugging particles settled in the fracture is the largest when the pumping rate is 0.04 m³·min$^{-1}$.

The pumping rate is proportional to the velocity of the proppant-laden fluid and particles after entering the rough fractures, so the particles under the large rate scheme mainly settle in F1; when the pumping rate decreases, the number of particles in F2 increases (Figure 5).
Figure 5. Settling results of temporary plugging particles in fractures under different pumping rates (a) 0.035 m³·min⁻¹; (b) 0.04 m³·min⁻¹; (c) 0.05 m³·min⁻¹.

We have studied the process of particle sedimentation at various pumping rates, and the results are shown in Figure 6. The stable time of the accumulation body is negatively correlated with the displacement, but positively correlated with the volume of the accumulation, and the longer the time, the closer the accumulation is to the export.

Figure 6. Accumulation process of temporary plugging particles in fractures at various rate (a) 0.035 m³·min⁻¹; (b) 0.04 m³·min⁻¹; (c) 0.05 m³·min⁻¹.

3.2. Effect of particle size combination
Particle size combination is also one of the factors that affect the sedimentation and accumulation of temporary plugging particles in rough fractures. There are 3 groups in this simulation experiment (Table 2). In the experiment, the pumping rate was selected as 0.05 m³·min⁻¹, the particles were mixed evenly and then added, and the concentration of temporary plugging particles was kept at 1%.

| Particle size combination (3 mm : 1 mm) | Pumping rate (m³·min⁻¹) |
|----------------------------------------|--------------------------|
| 3:3                                    | 0.05                     |
| 4:2                                    |                          |
| 5:1                                    |                          |

Figure 7 shows the sedimentation and accumulation of temporary plugging particles in rough fractures under different particle size combinations. It can be observed that the distribution of temporary plugging particles under the combined particle size conditions is significantly different.
from that of a single particle size. The volume of the temporary plugging particle accumulation at F2 is small, and the height is less than 1 cm. In the accumulation at F1, the two kinds of particles exhibited stratification, which is manifested as 1 mm particles covering the upper part of the 3 mm particle accumulation. In addition, when the particle size combination is different, and the morphology of the accumulation is different. The larger the proportion of 3 mm particles, the accumulation tends to be "hemispherical". However, the volume of the accumulation does not change regularly. When the mass ratio of 3 mm and 1 mm particles is 4:2, the volume of the accumulation is larger.

**Figure 7.** Settlement of particles in the fracture device under various particle size combinations (the black shaded part is the accumulation shape of 3 mm particles).(a)3 mm : 1 mm =3:3;(b)3 mm : 1 mm =4:2;(c)3 mm : 1 mm =5:1.

Figure 8 shows the sedimentation process of temporary plugging particles under the combined conditions of 3 mm: 1 mm=4:2 particles. It can be seen that in the early stage, mainly 3mm particles settled in F1, and the temporary plugging particles at F2 continued to decrease. As the particles settled, the accumulation volume continued to grow and moved to the export. At 45 s, the settlement of the 3 mm particles basically ended, and 1 mm particles began to appear on the top of the accumulation for 3 mm particles are large in mass and settle quickly, and 1 mm particles are suspended due to their small mass. After 3 mm particles settled, 1 mm particles began to slowly adhere to the surface of accumulation. This is also the reason for the stratification of the accumulation.

**Figure 8.** Sedimentation process of temporary plugging particles under combined particle size conditions.

### 3.3. Effect of the sequence of particle addition

The sequence of adding particles of different sizes has a greater impact on the rules of sedimentation and accumulation. After one particle size enter the device, add particles of another particle size to observe the migration and sedimentation of the particles. The particle size combination is 3:3 (to reduce the impact of particle quality), and the pumping rate is set to 0.05 m³·min⁻¹ (Table 3).
Table 3. Experiment scheme.

| Sequence               | Temporary plugging particle concentration (%) | Pumping rate (m²·min⁻¹) |
|------------------------|-----------------------------------------------|-------------------------|
| 1mm first, then 3mm    | 1                                             | 0.05                    |
| 3mm first, then 1mm    | 1                                             |                         |

It can be seen from Figure 9 that the sequence of adding particles of different sizes has a great influence on the final sedimentation morphology of the particles in the fractures. When adding 3 mm particles first and then adding 1 mm particles, the accumulation at F1 is mainly composed of 3 mm particles, a small amount of 1 mm particles cover the upper part of the accumulation and no particles appear at F2; When 1 mm particles are added first and then 3 mm particles are added, the accumulation at F1 are stratified, the bottom and top of the accumulation are 1 mm particles, and the middle is 3 mm particles. It can be found that the change of the sequence of adding different particle sizes mainly affects the sedimentation differentiation of the particles in the fractures. However, the accumulation is steeper and larger when the 3 mm particles are added first.

![Figure 9](image)

**Figure 9.** Accumulation morphology of temporary plugging particles under different adding sequence. (a) 3 mm first, then 1 mm; (b) 1 mm first, then 3 mm; (c) Comprehensive schematic diagram.

Compare the accumulation process of temporary plugging particles in the two sets of experiments to explore the influence of the sequence of addition. It can be observed that the rules of particle sedimentation and accumulation under the two adding sequence conditions are obviously different. Most of the 1 mm particles are mainly suspended and migrated and only some particles settle when the pump is injecting temporary plugging particles; after adding the 3 mm particles, the large particle size rapidly settles to form stratification. When the pump injection is completed, the suspended small particles settle again, forming a third layer of accumulation (Figure 10).

![Figure 10](image)

**Figure 10.** Settling process of temporary plugging particles in fractures under different adding sequence.
4. Conclusion
Pumping rate is inversely proportional to the stabilization time of the accumulation; accumulation will slowly move to the export, and the accumulation at F2 will gradually disappear; the accumulation at F2 gradually disappears; when the pumping rate is 0.04 m\(^3\)·min\(^{-1}\), the accumulation volume is the largest.

Under the combined conditions of different particle sizes, the 3 mm particles settle first, and the 1 mm particles settle later. The final performance is that the 1 mm particles basically cover the surface of the 3 mm particle accumulation. When 3 mm : 1 mm=4 : 2, the volume of the accumulation is larger.

The effect of the sequence of particle addition on the morphology of particle accumulation is mainly reflected in the layering of the accumulation. When adding 3 mm particles first and then adding 1 mm particles, the accumulation is dominated by 3 mm particles, and a small amount of 1 mm covers the upper part of the accumulation; there are 3 stratifications when the sequence is reversed, which is represented by 1 mm particles at the bottom and top, and 3 mm particles in the middle. However, the volume of the former accumulation is larger, and the amount of particle sedimentation is more.

In general, when the pumping rate is 0.04 m\(^3\)·min\(^{-1}\), the particle size combination is 3 mm:1 mm=4 : 2, and 3 mm is added first, temporary plugging particles have a larger volume of sedimentation in the fractures.

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