Experimental study of the temporary plugging pattern of perforations by multi-particle size composites

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Abstract. In the process of temporary plugging and diverting fracturing of horizontal wells, the seating of large-size temporary plugging balls on the perforation is unstable and the plugging efficiency of irregular perforations is low, so a smaller-size composite temporary plugging agent is needed to improve the temporary plugging efficiency. In this study, based on the actual situation of Changqing oilfield, three kinds of temporary plugging materials with small particle sizes were used to plug the perforation. A simulated perforation plugging device with different permeability was built by artificial cores, and the plugging law and pressure-bearing capacity of the composite temporary plugging materials inside the perforation were studied. The results show that the temporary plugging materials with particle sizes smaller than the diameter of the perforation can form a plug inside the perforation, and the plugging zone formed inside the perforation is discontinuous. The plugging zone has good pressure-bearing performance, and the indoor blocking pressure is more than 15 MPa. The orthogonal experiments showed that the importance of three kinds of temporary plugging agents in the composite temporary plugging materials were 3-4 mm particles, 0.15 mm powder, and 1-2 mm particles, and the optimal ratio is 3:3:2. This study provides a technical basis for the design of the temporary plugging and diverting fracturing.

1. Introduction
Multi-cluster fracturing technology for horizontal wells is one of the key technologies to achieve the efficient development of unconventional oil and gas reservoirs [1-2]. However, the perforation cluster efficiency is low in multi-cluster fracturing, and temporary plugging and diverting techniques are needed to seal the opened perforation clusters to force the fluid pressure in the wellbore to rise and press open other perforation clusters to form new fluid flow channels [3-5]. Conventional temporary plugging of the perforation uses a temporary plugging ball larger than the diameter of the perforation to seat and seal the perforation. However, because the diameter of the temporary plugging ball is designed to be 2.5 times larger than the diameter of the perforation [6], the temporary plugging ball cannot enter the interior of the perforation, which makes it difficult to ensure the stability of the seating. With the application of biodegradable materials [7-9], there is no need to worry about the reduction of production capacity because the temporary plugging agent cannot be degraded inside the perforation, therefore, the application of the temporary plugging agent with small particle size is promoted [10].
Since the contact between a single temporary plugging ball and the wall of the perforation cannot be completely made, especially for the irregular perforation caused by imperfect perforating or sand erosion, the temporary plugging effect is greatly reduced. Therefore, it is common to use different particle-size composite particles to carry out plugging. Studies on multi-grain composite temporary plugging agents are mostly focused on fracture sealing, and many scholars have made targeted preferences on the particle size and combination of temporary plugging materials [11-14]. In contrast, there are relatively few experimental studies on the temporary plugging of perforations, in which there are large discrepancies between the simulation of perforations and actual perforations [6]. The widely adopted method to simulate the perforation is to make a circular hole in the center of the metal plate and consider this hole as the perforation [15-16]. Based on this, a metal simulated perforation with a small core column size and a circular platform-like channel inside the metal to simulate a wedge-shaped perforation shape [17]. Since the simulated perforation device is made of metal, the fluid can only flow along the internal channels of the perforation and cannot simulate the filtration loss of fluid along the wall of the perforation during the sealing process. The method ignores the influence of formation permeability on the formation of temporary plugging.

In this study, we use an artificial core to make a permeable perforation device, and research the plugging law of multi-grain composite temporary plugging material in the perforation through dynamic temporary plugging experiments, to provide the technical basis for the design of temporary plugging and diverting fracturing operation.

2. Experimental methods

2.1. Experimental apparatus

Figure 1 shows the perforation temporary plugging simulation experimental system. The ISCO pump was used for liquid injection, with a maximum pumping rate of 100 mL/min and a maximum pumping pressure of 70 MPa. The carrying fluid containing temporary plugging material was placed in an intermediate container with a maximum volume of 5 L. The whole device was connected by a high-pressure-resistant pipeline. During the experiment, the injection pressure at the injection end and the flow rate at the exit end of the perforation were collected in real-time.

![Perforation temporary plugging simulation experimental system](image)

Figure 1. Perforation temporary plugging simulation experimental system.

To simulate the fluid filtration loss at the wall of the perforation, the artificial core was used to make a simulated perforation in the experiment, as shown in Figure 2. The whole artificial core is 30×30×10 cm³ in size, divided into three parts, which are compacted by quartz sand of different grain sizes with different permeability. The center of each of these three sections has a semi-conical groove to simulate a perforation with an entrance diameter of 1.6 cm. The surface of the artificial core is sealed with a rubber gasket to prevent fluid flow along the surface of the core before the experiment. The backside of the simulated perforation device has three holes facing the center of each of the three
sections of the artificial core, and the fluid entering the core is exported to the collection device through a pipe (see Figure 2). An electronic balance was used to measure the liquid flowing from the perforation.

![Figure 2. Interior and exterior view of the simulated perforation device.](image)

2.2. Diverters
According to the experience of Changqing oilfield, a temporary plugging system consisting of three particle sizes mixed and compounded, in which the temporary plugging material has the characteristics of high strength, high toughness, and self-dissolving. The indexes of the materials are shown in Table 1, and the three particle size temporary plugging materials are shown in Figure 3.

| Parameters                   | value                        |
|------------------------------|------------------------------|
| Particle size                | 0.15 mm, 1-2 mm, 3-4 mm      |
| Density (g/cm³)              | 1.32                         |
| Bulk density (g/cm³)         | >0.9                         |
| Thermal stability (℃)        | >250                         |
| Elastic Modulus (GPa)        | >1.6                         |
| Compressive strength (MPa)   | >70                          |
| Solubility (%)               | Complete dissolution in 4 days under alkaline conditions at a formation temperature |

![Figure 3. Three kinds of diverters.](image)

2.3. Experimental procedures
Since the pumping rate used in the field is much larger than the maximum pumping rate that can be achieved in the indoor experiment, to ensure the carrying performance of the liquid to the diverters,
the indoor experiment uses the cross-linked guar fracturing fluid system as the carrying fluid. The experimental procedures are as follows:

1) Prepare the carrier fluid as the formula shown in Table 2. Add various diverters according to the design during the mixing process.
2) Place the carrier fluid in the intermediate container and pump it with a fixed flow rate.
3) Stop pumping when the injection pressure reaches 15 MPa.
4) Observe the sealing of the interior of the perforation after pressure is removed.

### Table 2. Formulation of guar gum base solution

| additives   | Thickener | Cosolvent | pH conditioner | Crosslinker |
|-------------|-----------|-----------|----------------|-------------|
| Name        | Hydroxypropyl guar gum | Citric acid | YC-150 | ZFJ-8793 |
| Concentration (g/mL) | 0.2% | 0.02% | 0.12% | 0.25% |

### 3. Results and discussion

#### 3.1. Temporary plugging of a single perforation
To investigate the effect of different permeability of the reservoir on the plugging of the perforation, and to optimize the combination of three particle size temporary plugging materials, the experiment firstly investigated the plugging law when opening a single perforation. The orthogonal experiments were conducted to analyze the influence of permeability and three types of temporary plugging materials on the plugging effect, and an orthogonal test with a four-factor, three-level was designed to optimize the ratio of temporary plugging materials. Since the concentration of temporary plugging material is large enough to cause blockage of wellbore or pipeline, the concentration of temporary plugging material is set low, including 0.5%, 1.0%, and 1.5%. The experimental factors and levels are shown in Table 3. The following nine sets of orthogonal tests were designed according to the four factors and three levels, and the specific parameters are shown in Table 4.

### Table 3. Experimental factors and levels.

| Factor Level | Permeability (mD) | The concentration of 0.15 mm powder (g/mL) | The concentration of 1-2 mm particles (g/mL) | The concentration of 3-4 mm particles (g/mL) |
|--------------|-------------------|--------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1            | 50                | 0.5%                                       | 0.5%                                        | 0.5%                                        |
| 2            | 500               | 1.0%                                       | 1.0%                                        | 1.0%                                        |
| 3            | 2500              | 1.5%                                       | 1.5%                                        | 1.5%                                        |

### Table 4. The scheme of the temporary plugging experiments.

| No. | 0.15 mm powder | 1-2mm particles | 3-4mm particles | Permeability |
|-----|----------------|-----------------|-----------------|--------------|
| No.1| 0.5%           | 0.5%            | 0.5%            | 50           |
| No.2| 0.5%           | 1.0%            | 1.0%            | 500          |
| No.3| 0.5%           | 1.5%            | 1.5%            | 2500         |
| No.4| 1.0%           | 0.5%            | 1.0%            | 2500         |
| No.5| 1.0%           | 1.0%            | 1.5%            | 50           |
| No.6| 1.0%           | 1.5%            | 0.5%            | 500          |
| No.7| 1.5%           | 0.5%            | 1.5%            | 500          |
| No.8| 1.5%           | 1.0%            | 0.5%            | 2500         |
| No.9| 1.5%           | 1.5%            | 1.0%            | 50           |

As can be seen from the series of temporary plugging experiments, changing the ratio of temporary plugging materials does not directly affect the pressure-bearing capacity of the plugging structure, and the maximum pressure-bearing capacity of the plugging is greater than 15 MPa in the experiments (Figure 4). However, the change in the ratio of temporary plugging material will cause the difference in plugging efficiency, which is reflected in the different time and liquid injection volumes used to achieve the same plugging capacity.

When the compound temporary plugging of multi-particle size materials, the main rule of sealing in the perforation is that the large particles bridge and the small particles fill. As can be seen from the
pressure curve in Figure 4, when the concentration of 3-4 mm particles is 1.5%, the injection pressure of the three groups of tests starts to rise significantly within 5 min. This is because the concentration of large particles is relatively large, which rapidly completes the bridging inside the perforation and brings resistance to the liquid flow. When the large particles finish bridging, the gaps formed between the particles need to be filled by small particles in time to form a dense blocking zone, which reduces the permeability of the blocking zone and makes the injection pressure rise. Comparing tests No.3, No.5, and No.7, we can see that the different concentrations of 0.15 mm powder in the three test groups lead to a significant difference in the rate of pressure rise. This indicates that the different particle size temporary plugging materials need to be matched in the right ratio to seal the perforation efficiently.

![Figure 4. Experimental pumping pressure comparison chart.](image)

### 3.2. Analysis of orthogonal experiments

The temporary plugging efficiency can be evaluated by comparing the time when the repellent pressure reaches 15 MPa in different experimental groups. The results of the orthogonal test are shown in Table 5, and the main relationship between the four factors on the temporary plugging efficiency is 3-4 mm particle concentration > 0.15 mm powder concentration > 1-2 mm particle concentration > core permeability. The optimized concentration combination of the three particle size temporary plugging materials is: 1.5% 3-4 mm particles + 1.0% 1-2 mm particles + 1.5% 0.15 mm powder.

| No.  | 0.15 mm powder | 1-2 mm particles | 3-4 mm particles | Permeability | Time-consuming when fracturing reaches 15 MPa (min) |
|------|----------------|------------------|------------------|-------------|-----------------------------------------------|
| No.1 | 1              | 1                | 1                | 1           | 46.2                                          |
| No.2 | 1              | 2                | 2                | 2           | 29.3                                          |
| No.3 | 1              | 3                | 3                | 3           | 24.2                                          |
| No.4 | 2              | 1                | 2                | 3           | 23.4                                          |
| No.5 | 2              | 2                | 3                | 1           | 14.3                                          |
| No.6 | 2              | 3                | 1                | 2           | 38.6                                          |
| No.7 | 3              | 1                | 3                | 2           | 12.1                                          |
| No.8 | 3              | 2                | 1                | 3           | 34.1                                          |
| No.9 | 3              | 3                | 2                | 1           | 23.2                                          |
| K1   | 99.7           | 81.7             | 118.9            | 83.7        |
| K2   | 76.3           | 77.7             | 75.9             | 80          |
| K3   | 69.4           | 86               | 50.6             | 81.7        |
| k₁   | 33.2           | 27.2             | 39.6             | 27.9        |
| k₂   | 25.4           | 25.9             | 25.3             | 26.7        |
| k₃   | 23.1           | 28.7             | 16.9             | 27.2        |
| R    | 10.1           | 2.8              | 22.8             | 1.2         |
From the analysis results, it can be seen that the effect of core permeability on the temporary plugging efficiency is not significant. This is due to the larger permeability of the artificial cores used in the tests, in which the flow resistance of the carrying fluid is smaller. In particular, the same pumping rate was used in all tests, i.e., the same fluid feeding capacity of the perforation was simulated, so when there is no significant difference in fluid feeding capacity between perforations, there will be no significant difference in their plugging efficiency.

After the test, the simulated perforation device was opened, and the accumulation of temporary plugging materials in the perforation can be observed, as shown in Figure 5. The sealing position formed by the temporary plugging material inside the perforation may be discontinuous (such as tests No.1, No.5, No.6, and No.7 in Figure 5).

![Figure 5. Blockage inside the perforation in each experiment (white parts in the perforation are the temporary plugging agents).](image)

4. Conclusions
The research on the plugging law of the perforation with multi-grain composite temporary plugging materials is carried out through dynamic temporary plugging experiments, which provide the basis for the optimal design of temporary plugging and diverting fracturing scheme.

1) Due to the permeability of the reservoir, small size temporary plugging materials can also form a plug inside the perforation, and the plugging zone formed by the temporary plugging materials inside the perforation is discontinuous.

2) The degree of influence of different particle size temporary plugging materials on plugging efficiency is 3-4 mm particles > 0.15 mm powder > 1-2 mm particles.

3) The preferred ratio of the three particle size temporary plugging materials is 3-4 mm particles: 1-2 mm particles: 0.15 mm powder = 3:2:3.

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