Mechanism of migration and settlement for temporary plugging ball in shale gas horizontal wells

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Abstract. In order to determine the migration and settlement mechanism of temporary plugging balls in horizontal wells, the rules for distribution, migration and settlement of balls in different location were researched through calculation, coupling fracturing fluid and characteristics of movement based on CFD (computational fluid dynamics), DEM (discrete element method) and DDPM (dense discrete phase model), and the intensity, plane and spatial distribution of the microseismic events before and after ball-addition were analysed. The results showed that: First, the central flow core in the pipeline is the main migration carrier of the temporary plugging balls and proppants, low-viscosity liquid performs differences when inflowing at various perforation holes. The settlement and plugging in downstream cannot be effectively improved while the upstream without balls' settlement. Second, due to the fluid resistance, the mean velocity of temporary plugging balls decreases and balls spread along the casing wall while the interaction force can be ignored. Under different displacement, the temporary plugging balls' migration speed has a relatively stable value, the displacement of 5 m^3/min is the critical value for the effective setting of temporary plugging balls. Thus, most of the micro-seismic events after ball-addition were concentrated in the upstream clusters, the impact scope of the micro-seismic events of 6-clusters is greater than that of 8-clusters perforation. After ball-addition in 6-clusters, the key effect is to improve the complexity of the microfracture network, while in 8-clusters to improve SRV (simulated reservoir volume) for the beginning first 4 clusters. So that is, increasing the number of clusters will lead to an inadequate microfracture length extension and only SRV (simulated reservoir volume) near the wellbore zone was improved.

1. Introduction
China's commercial development shale gas is increasing in recent years, and hydraulic fracturing of horizontal perforation well has become the main technology[1-3]. The temporary plugging ball addition technology is widely used in cluster's plugging and refracturing of old wells. As to this technology, large particle temporary plugging balls are used for plugging the perforations in the casing, and then the fluid is branched after temporary plugging to exploit new reservoir[4-5]; the fluid is medium to form unimproved areas, fracturing microfractures and expanding the reservoir reconstruction system[6-9]. The temporary plugging material is water-soluble and the plugging of the perforation can be released after a certain period of time, so the later development of the reservoir will not be affected. Previous studies have shown that, through addition of temporary plugging balls, plugging of perforations on the casing can be performed, the reservoir fluid dynamic pressure can be increased rapidly, and promote fracture complexity[10-15].
At present, in the research on temporary ball plugging technology at home and abroad, there is a lack of research on the rules of migration and the setting and plugging effect of temporary plugging balls[16-20]. In-situ construction cannot determine the position of temporary ball plugging and the effectiveness. There is also a lack of corresponding laboratory evaluation method[21-24]. Therefore, in this paper, research on the migration and setting mechanism of temporary plugging balls is carried out for the purpose of obtaining the theoretical basis for explaining the characteristics of field construction.

2. Distribution of liquid flow patterns

2.1. Liquid flow in horizontal casing

For most of the shale gas wells in Fuling area, their horizontal stage is more than 1000 m. The staged perforation is employed in the hydraulic fracturing reconstruction. In order to achieve rapid forming of fractures, large displacement dragging water pumps are often used for pumping, and the fluid volume in a single stage can reach more than 3000 cubic meters. Therefore, the flow velocity and pressure distribution of fluid when it flows through the horizontal stage and the perforation hole are different from those of a conventional well or a vertical well. The effect of gravity on the solid phase components is more apparent. In particular, under a low flow velocity, the high viscosity polymer, proppant subsidence and temporary plugging balls tend to settle and cause uneven distribution.

CFD was used for calculation, and a casing with a size of 5.5 inches, a diameter of 118mm, a length of 100 m and an inlet flow velocity of 20 m/s was simulated, and 0.04% water drag reduction in liquid phase was used. The calculated results were shown in figure 1 with the image scale being adjusted. It can be seen that the wall effect leads to the obvious shear stress area near the wall of the casing, and the intermolecular friction increases, the flow velocity decreases, and the liquid efficiency decreases. Due to the linear macromolecular polymer in the field liquid system, the friction coefficient between macromolecules is small and agglomeration occurs. A stable flow core is formed in the centre of the casing. For the small velocity differences inside, the flow core is the main migration section of the temporary plugging balls and the proppant.

In order to effectively load the solid particles, the viscosity of liquid phase should be appropriately increased. This can reduce the spatial size of the laminar flow zone and the transition zone, increase the proportion of the central flow core, and keep a stable velocity of the liquid phase and the solid phase.

2.2. Liquid flow in perforation section

The shale gas horizontal wells in Fuling area mostly adopt the spiral perforation holes, with 2-5 clusters in each stage, the hole density is mostly 16 holes per meter and the diameter is 9mm. In order to study the fluid morphology in the perforation stage, a casing with 5 m / 3 clusters / 42 holes was set up. The N-S equation was used for calculation to obtain the cross-section flow pattern comparison diagram at different flow rates as shown in figure 2.
The calculation results show that the liquid branching effect is obvious along the axial direction of the perforation, and the velocity distribution changes non-linearly at different flow rates. In the case of small displacement, it can be seen that the branching range of the upstream perforation is large; in the case of large displacement, the branching range of the downstream perforation is large.

2.3. Liquid flow in long horizontal casing with multi-cluster perforation

The fluid in a long horizontal stage enters each cluster in turn after being decelerated in the round pipe stage. The branching effect of each cluster is related to the cluster spacing and the number of clusters. A perforation model for the long horizontal stage was established, with a length of 100 m, there were 3 clusters of perforation holes, the hole density 16 holes per meter, 16 holes per cluster, and cluster spacing is 23 m. Free boundaries were set at each cluster of holes, 1 to 3 clusters from left to right. The absolute flow rate at each point was observed and compared with the liquid efficiency. The calculated results after the image scale was adjusted are as shown in figure 3.

It can be seen from the results that after passing through the perforation, the liquid flow velocity decreases significantly. The loss of liquid kinetic energy at each cluster of perforation holes is more than 50%. In the free flow state, an increase in displacement has little influence on the flow velocity of the third cluster. The average flow velocities in the sections are all less than 6m/s, indicating that the sweep efficiency of liquids deep in the reservoir is reduced.

3. Law of temporary plugging ball’s migration and settlement

3.1. Migration and settlement of temporary plugging ball in horizontal casing
A CFD and DEM liquid-solid coupling model was established to simulate the casing with a size of 5.5 inches, an inner diameter of 118mm, a length of 100m, an inlet flow rate of 20m/s, and the liquid phase was a drag reducing water with 0.04% concentration. The density of the temporary plugging ball: 1.5 g/cm³, diameter: 13.5 mm, number of balls: 20.

The calculation results are as shown in figure 4. The results show that the temporary plugging balls cluster and enter the manifold, the pressure inside the casing increased, and the velocity increased immediately after the ignition. Being limited by the fluid resistance, the velocity of the temporary plugging balls decreases, the spatial distribution becomes different, and the temporary plugging balls spread along the casing wall. The particles spread after a migration of 10 m, and the force between the temporary plugging balls is ignoble.

![Figure 4. Mean velocity of temporary plugging balls in horizontal casing.](image)

Once the temporary plugging balls were in stable migration along the casing wall, their average velocity was 17-18 m/s. Therefore, there may be orientation selectivity in the temporary plugging addition diverting process. The migration speed of the temporary plugging balls under different displacement rates has a relatively stable value.

3.2. Migration and settlement of temporary plugging ball in perforation section

At the perforation hole, the local water-head loss is large, and the flow rate changes dramatically. The temporary plugging ball at the perforation hole is affected by forces in all directions, so it is impossible to carry out the calculations with the simplified model for single particle. The simulation calculation is performed with DDPM to track the migration route of the temporary plugging ball particles. In this way, a rough can be gained on the influence exerted by the fluid drag force at the perforation on the temporary plugging balls. The trajectory shape of the temporary plugging ball in the casing is not considered in the calculation. Particles are released at the centre of the casing inlet to track the changes in the particle velocity and displacement. The number of perforation hole was 16. The gravity was considered. The density of the temporary plugging ball is 1.5 g/cm³. The displacement was increased step by step. The fluid flowed out at the outlet freely. The calculation results are as shown in figure 5 below.

![Figure 5. Trajectory of temporary plugging ball’s transport in perforation section.](image)
According to the results, effective settlement of the temporary plugging ball occurs under various displacements. This indicates that the effect of gravity is stronger than the attraction of the perforation holes, and that all the solid particles show obvious liquid velocity-correlative characteristics. When the displacement is more than 5 m³/min, the particles can directly perforate through this hole cluster and cannot be effectively set, that is, the displacement of 5 m³/min is the critical value of the effective setting of the temporary plugging ball. After the temporary plugging ball has settled and is close to the perforation hole, it can be set directly. Therefore, it can be inferred that the prerequisite for effective setting of the temporary plugging ball is that it should be close to the lower edge of the casing wall.

4. Analysis of engineering case
In a horizontal shale gas well with multi-cluster spiral perforation completion, the reconstruction effect is affected by factors such as the direction of ground stress, curvature and fault, and the reconstruction effect varies significantly. The setting position of the temporary plugging ball is the perforation holes on the wellbore. Different from the temporary plugging diversion mechanism in the temporary plugging agent, the rules of migration and plugging for solid particles in the wellbore are obviously different. The oriental selectivity of the temporary plugging balls will inevitably result in some of the perforations still receiving fluid, and the perforation in the cluster will receive fluid unevenly. Figure 6 shows the layout of the microseismic events in the 9th/10th two-stage construction. The events in magenta are the monitoring results before the ball addition, and the events in dark green are the event responses after the ball addition.

![Microseismic events before and after ball addition](image)

Figure 6. Horizontal distribution map of the microseismic events in the 9th/10th stages.

As can be seen from the results, 6-cluster perforations were adopted in the 9th stage. Before the ball addition, the micro-seismic events were mostly distributed in the perforation in the middle part of the stage and the event distribution was relatively average, with a large area enveloped by the event points. After the ball addition, a large number of events occurred in the first 3 clusters close to the direction of Target A, with a small affected area. This indicates that the liquid efficiency acted on the first 3 clusters after burling of the temporary plugging balls, and the action space at the ignition time of 6 clusters is selective. In the 10th stage, an 8-cluster perforation was used. Most of the micro-seismic events before the ball addition occurred in the middle and rear perforations, the events were concentrated in the near-well zone, and the branch fracture expansion was not obvious. After the ball addition, the events also occurred in the first 4 clusters close to Target A. After burling of the temporary plugging balls, most of the liquid entered the first 4 clusters for secondary reconstruction.
No event points were found in the last 4 clusters, which indicates that this region was not reconstructed.

5. Conclusion
1) The center flow core area of the casing determines the migration pattern of the temporary plugging balls. The liquid viscosity affects the large flow core area. Branching of a low-viscosity liquid is obvious at the perforations, and it can easily enter the front end of the perforation to play the role of reservoir reconstruction. Because of the selectivity of liquids, the ball bitching should be used to plug the upstream perforations near the end and branch the fluid from top to bottom.

2) The velocity of the temporary plugging ball decreases in the casing, and they have the orientation selectivity. The prerequisite for their effective setting is to come close the casing wall. The calculation results show that under a displacement of 5m³/min the temporary plugging ball will settle obviously and set in the perforation area, so this is the effective displacement for the temporary plugging ball addition. If the displacement is too large, the balls can be easily carried into the far end, and effective plugging of the far end of the perforation will not be possible.

3) The micro-seismic events can reflect the effect of the temporary plugging ball addition. 6-cluster perforations are adopted, and event coverage radius is large. After the ball addition, the main work is to improve the complexity of near-wellbore fracture network. The 8-cluster perforations were used to reduce the coverage radius. The fracture length was increased and the fracture length extension was promoted after the ball addition. The micro-seismic events after the ball addition have mostly occurred in the upstream perforations, which indicate that the temporary plugging ball addition under high displacement has a poor effect on the secondary reconstruction of the downstream deep reservoir.

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