Study on the multicomponent collaborative sealing mechanism of shale formations

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Abstract. Due to strong inhibitive ability, oil-based drilling fluid system was often the first choice of drilling fluids in the drilling operation of shale plays. However, borehole instability problems tend to occur most frequently in the drilling operation of horizontal well intervals. So the sealing mechanism of shale formation was of great importance to wellbore stability. Sealing effect of colloid particles, bridging and blocking effect of skeleton particles, plugging function of deformable particles and isolation effect of polymer were analysed, and multicomponent collaborative plugging mechanism was investigated. The results indicated that it could play an important role in plugging micropores and microfractures on shale surface to form a blocking layer with ultra-low permeability. This study can be helpful for the design of novel plugging agents for drilling fluids, and endow with economically and technically viable petroleum development and production.

1. Introduction
Oil-based drilling fluid system has strong inhibitive ability, and it can prevent shale formations from hydration and swelling, and thus is often used in the development of gas reservoirs [1-6]. Although oil-based drilling fluids are very suitable for the drilling operations of shale gas wells, borehole instability problems occur easily in the drilling operation of horizontal intervals [7-10].

Maintaining wellbore stability is the most critical aspect of drilling operations of horizontal well intervals [11-14]. However, most of oil-based mud (OBM) could not prevent filtrate invasion into micropores and microfractures on shale surface, and subsequent cause borehole instability problems. The main reason is that conventional drilling fluid particles are too large to seal the micropore throats or microfractures in shale formations, and thus could not stop fluid invasion [15-19].

The sealing mechanism of shale formation is of great importance to the development of novel plugging agents for drilling fluids. Plugging effect of colloid particles, bridging and blocking effect of skeleton particles, plugging function of deformable particles and blocking partition of polymer are analyzed, and multicomponent collaborative plugging mechanism is investigated, too. Specifically, colloid particles could block micropores and capillary fractures, rigid skeleton particles could bridge in the microfractures, deformable particles could block or fill the channels of microfractures, and
polymer could generate blocking partition, finally forming sealing layer with ultra-low permeability, so it can play an important role in plugging micropores and microfractures on shale surface.

2. Research on the sealing mechanism of shale formations

Due to a large number of micropores and microfractures in shale formations, the invasion of filtrate or drilling fluids into micropores and microfractures could cause pressure transmission, and lead to borehole instability. Therefore, the effective sealing of the micropores or microfractures on the borehole wall in shale formations to stop the pressure transmission is the key for the improvement of wellbore stability. More importantly, the sealing mechanism of micropores or microfractures in shale formations should be known to solve borehole instability problem at first.

The micropores in shale formations are between nanometer and micrometer. The microfractures are composed by capillary fracture (width<10 µm) and microscopic checks (width=10~100 µm), as shown in Figure 1. For the sealing of micropores and capillary fractures, the sealing mechanism should be investigated from the plugging effect of colloid particles. For the sealing of microscopic checks, the sealing mechanism should be investigated from the multicomponent collaborative plugging mechanism.

Figure 1. Scanning electron images of shale samples from west China.

2.1. The sealing effect of colloid particles

The partical size of colloid particles is around 0.001~0.1 µm, so they can easily enter and seal the micropores and capillary fractures in shale formations. The particle size distribution of a kind of colloid particles is shown in Figure 2. The medium diameter of these colloid particles is 0.1115 µm, D_{10} is 0.0741 µm, and D_{90} is 0.1646 µm, and thus they can seal the micropores and capillary fractures easily.

Figure 2. The particle size distribution of colloid particles.
2.1.1. The effect of plugging porous channels. The particle size of colloidal particles is less than 0.1 µm, so they are small enough to enter the pore throat of rocks, and plug the micropores and capillary fractures on the borehole wall. As shown in Figure 3, due to strong plugging pore effect, the colloidal particles can seal the micropores and capillary fractures of shale formations, forming thin and tight internal mudcake deposited on the borehole wall, and thus reducing the permeability of the borehole wall, minimizing filtrate invasion into shale formations, and improving wellbore stability.

![Figure 3. The schematic of plugging pore of colloidal particles.](image)

2.1.2. Improving mudcake quality. The colloidal particles have strong ability of plugging pore, so they can block and seal the residual pore throats of mudcake easily, and form thin and tight mudcake. As a result, an effective mudcake could be built, the mudcake quality could be improved significantly, the permeability of mudcake could be decreased, and HTHP filtration of drilling fluids could be minimized greatly.

2.2. The bridging and blocking effect of rigid skeleton particles

2.2.1. Bridging and blocking effect. Based on 1/2~2/3 bridging theory, the rigid skeleton particles with a diameter of 5~66 µm could enter the microscopic checks with a width of 10~100 µm. They could be adsorbed and captured by the microscopic checks, and blocked on the surface of microfractures. The particle size distribution of a type of rigid granular material is showed in Figure 4. The medium diameter of this rigid material is 14.976 µm, D_{10} is 4.8396 µm, and D_{90} is 35.439 µm, so these rigid skeleton particles could enter the microscopic checks, and play an important role in bridging and blocking.

![Figure 4. The particle size distribution of rigid granular materials.](image)
2.2.2. **Gravitational settling function.** The rigid skeleton particles could be subsided on the surface of microfractures in the gravity field. A portion of rigid skeleton particles flip toward the horizontal direction, and they could be captured by fractures, thus reducing the width of microfractures. A portion of rigid skeleton particles flip toward the vertical direction, and they could be captured by fractures, thus reducing the porosity of microfractures.

In addition, after the fractures are plugged by deformable material and natural macromolecule polymer, the rigid skeleton particles could enter and block the residual minute pore in the process of the sealing of fractures, too, and generate tight packing layer, as shown in Figure 5. Meantime, the rigid skeleton particles could improve the intensity of mudcake formed at HTHP conditions, and strengthen the sealing effect.

![Figure 5](image-url)  
**Figure 5.** The schematic diagram of filling of rigid granular materials.

2.3. **The plugging function of deformable particles**

The deformable particles could be expanded upon imbibing oil, and they have good elasticity and toughness. The deformable particles with a diameter of less than 76 µm could be squeezed into the channels of microfractures with a width of 10-100 µm under the influence of differential pressure. They could be expanded by imbibing oil or shrink in volume with the change of bottom hole pressure.

When the particle size of deformable particles is bigger than the fracture width, the deformable particles could be squeezed into the channels of fractures, and thus blocking the fractures by its own elastic deformation. When the particle size of deformable particles is less than the fracture width, the deformable particles could be captured by fractures, thus accumulating and bridging on the surface of fractures. These deformable particles could be expanded by oil absorption, so they could fill and seal the pore throat of fractures. The process of microfractures sealed by two kinds of deformable particles is shown in Figure 6.

When the differential pressure is increased, the deformable particles could seal the microfractures by their own elastic deformation. When the differential pressure is reduced, the deformable particles could recover their original elasticity, and thus could be tightly integrated with fractures. Therefore, the deformable particles have double characteristics of blocking and filling, and are adaptable to the sealing of microfractures with different shapes and sizes.

![Figure 6](image-url)  
**Figure 6.** Two sealing modes of microfractures sealed by deformable particles.
2.3.1. *The effect of inlaying and plugging.* The deformable particles could alter its own shape on the basis of the entrance dimension of channels of microfractures, so they could be inlaid and tightly integrated with sides of fracture, and thus play an important role in plugging the fractures.

2.3.2. *The effect of elastic expansion.* When the microfractures have been plugged by the deformable particles, the deformable particles could release their elastic energy with the reduction of bottomhole differential pressure, and the volume of deformable particles could be expanded and extended. So the deformable particles could occupy the space that was not previously occupied, further strengthening the plugging effect of the channels of fractures, and thus improving the plugging intensity.

2.4. *The blocking and isolating effect of macromolecule polymer*

The macromolecule polymer has a certain softening point, and it could be softened and deformed at high temperature. The isolating membrane could be formed on the borehole wall of shale formations by physical absorption at high temperature, the compactness of mudcake could be enhanced, and the adhesive force between the plugging materials and borehole wall could be improved. The blocking and isolating process of macromolecule polymer is shown in Figure 7.

![Figure 7](image)

**Figure 7.** The diagram of the sealing mechanism of macromolecule polymer.
A—Macromolecule polymer  B—Polymer accumulated on borehole wall  C—Isolating film with low permeability to restrict fluid penetration

2.4.1. *The adsorption effect.* The macromolecule polymer dispersed in drilling fluids is gathered around the borehole wall of shale formations under the influence of differential pressure. They could be adsorbed on the surface of borehole wall by physical interaction at high temperature.

2.4.2. *The barrier effect.* The macromolecule polymer could be softened and deformed at high temperature, and the isolating barrier could be formed on the surface of borehole wall of shale formations, thus reducing fluid invasion into the shale formations by a significant amount.

2.4.3. *The effect of penetration limitation.* The macromolecule polymer has good viscoelasticity at high temperature, so the skeleton material and deformable particles on the borehole wall could be bonded together, and an isolating film could be formed, thus preventing filtrate invasion into shale formations.

2.5. *The multicomponent collaborative plugging mechanism*

The micropores and microfractures in shale formations could be sealed by the multicomponent collaborative plugging effect of colloid particles, rigid skeleton material, deformable particles and
macromolecule polymer. The colloid particles could seal the micropores and capillary fractures, the rigid skeleton material could seal the microscopic checks by the bridging and blocking effect, the deformable particles could seal and fill the channels of microfractures, the macromolecule polymer could form an isolating membrane, and thus an isolating layer with low permeability could be formed.

![Diagram of Multicomponent Collaborative Plugging Mechanism](image)

**Figure 8.** The diagram of the multicomponent collaborative plugging mechanism.

The multicomponent collaborative plugging mechanism is shown in Figure 8. Firstly, the colloid particles enter the micropores and capillary fractures, so the micropores and capillary fractures around the borehole wall could be sealed, and an effective mudcake of high quality could be formed. Secondly, the rigid skeleton particles are captured by the surface of microfractures, and they could be bridged in the fractures through bridging and blocking effect and gravitational settling function, so the primary plugging for microfractures could be generated. Thirdly, the deformable particles could seal and fill the channels of microfractures through the effect of inlaying and plugging and the effect of elastic expansion. Fourthly, the macromolecule polymer could form an isolating membrane though the adsorption effect, the barrier effect and penetration limitation. Finally, the colloid particles, rigid skeleton material, deformable particles and borehole wall could be bonded together by the macromolecule polymer at high temperature. An isolating layer with low permeability could be formed, and the micropores and microfractures in shale formations could be sealed effectively.

3. Conclusions

1) The sealing of micropores or microfractures on the borehole wall of shale formations to prevent pressure transmission is the key to improving wellbore stability.

2) The plugging effect of colloid particles, bridging and blocking effect of skeleton particles, plugging function of deformable particles, and blocking and isolating effect of macromolecule polymer could play an import role in plugging micropores and microfractures on shale formations.

3) The multicomponent collaborative plugging mechanism is of great importance to wellbore stability. An isolating layer with low permeability could be formed on the borehole wall, and it can meet the requirement of sealing different classes of micro-pored and micro-fractured shale formations.

Acknowledgment

This study is supported by the National Science and Technology Major Project (No. 2016ZX05020-004, 2016ZX05051, 2017ZX05030-004, 2015M571228) and CNPC Project (No. 2018E-18, 2018D-5009-05, 2017D5008-03, 2016E-0109, 2016E-0608).

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