Development of responsive well plugging material in carbonate reservoir

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Abstract. One of the most critical problems limiting the exploration and development of the Central Asia and Middle East Areas is lost circulation caused by the natural fracture propagating in carbonate reservoir. Traditional plugging materials had limited performance due to poor adaptability to carbonate formation. This paper investigated the mechanism of lost circulation in Central Asia and Middle East Areas, and a new responsive fracture plugging materials was developed. After implementation, the complexities treatment time was shortened and drilling efficiency was increased. The main types of lost circulation mechanism are summarized and analysed by studied the reservoir characteristics of Central Asia and Middle East Areas. A physical model of horizontal V funnel leakage channel in the target block was established to simulate the migration and plugging process of plugging particles in natural fractures. Based on the analysis of the flow and accumulation pattern of the plugging fluid in the leakage channel with different aperture ratio, a statistical model of the particle flow in the plugging material was established. A response controllable solidification plugging material was developed. The application results show that, the responsive solidification controllable well plugging material could rapidly accumulate in the 1mm and 3mm fractures in the upper sealing formation. The mud cake has good toughness with compressive strength of 3.4-9.5MPa, which achieves a rapid and high-strength plugging for the fracture formation. The acid soluble consolidation plugging material, mainly composed of curing agent, retarder, suspending agent, etc., is developed for long open hole section. The dissolution rate could reach up to 91%, the plugging strength of the solidified plug is up to 10MPa and which could be stable for 15d under 150°C. This innovative anti-lost circulation materials for carbonate reservoirs can effectively solve the problem of serious loss of production due to sever lost circulation problem in the Mishrif reservoirs of Central Asia and the Middle East and enhance the drilling of complex carbonate oil and gas fields. The implementation of this plugging material improves the technical level of drilling and completion of complex carbonate oil and gas fields and
provides strong support for exploration and development in Central Asia and the Middle East.

1. Introduction

Central Asia and Mid-East, as the hot spots of China National Petroleum Corporation (CNPC)’s oversea investment area, are the main battlefields for CNPC to achieve its overseas production capacity targets. It plays an important role for supporting CNPC’s overseas oil and gas business goals. During the 13th Five-year development plan, CNPC has drilled more than 5,000 wells in Central Asia and the Middle East areas, which takes 60% of the CNPC oversea wells. According to prediction in 2020, China’s foreign dependence on oil and gas will reach 70%. Central Asia and the Middle East will be the main regions of China's overseas oil and gas production and imports.

The main drilling difficulty in Central Asia and the Middle East is lost circulation. In Central Asia region, where the fractures of the hydrochloride rock reservoir are developed, the stratum is broken, and the formation porosity is high, which leads to the simultaneous occurrence of severe lost circulation and well kick. In the Middle East region, Carbonate strata have strong heterogeneity. The fracture caves are developed, and the pressure window of drilling fluid is narrow (0.02g/cm³). The serious drilling losses occurs frequently, which disastrously restricts the progress of exploration and development in Central Asia and the Middle East. To overcome the lost circulation complexity in fracture-cavity carbonate formation, the mechanism of lost circulation is studied, and a responsive well plugging material is developed in this paper. The problem of loss circulation during drilling the upper formation and long horizontal section is solved.

2. The mechanism of lost circulation in the central Asia and Middle East

Investigation shows that, the typical lost circulation in carbonate formation is category as follows: fracture induced, fracture expansion loss and cavernous formations [1].

Fracture induced: The wellbore exposes to the closed fractures [2]. During the drilling process, the wellbore pressure is high, causing the formation to rupture or cracks to open, resulting in artificially induced fractures, the loss of drilling fluid induced. Fracture expansion: There are non-leakage natural fractures with small openings in the exposed formation, which gradually widens under the action of pressure, temperature, fluid flow, etc., and eventually forms leaky fractures and loses. Cavernous formations: The formation of cracks and karst caves in the exposed formation of the wellbore causes the size of the loss channel to become larger, and the drilling fluid can flow into the formation freely under the action of the pressure difference.

Most of the drilling lost circulation problems occurred in the Amu Darya River region are in the Oxford-Karovian stage formation, which could mainly be divided into three fracture-karst cave type layers, as shown in Figure 1 [3]. The first layer, micro-cracks and karst caves are developed the porosity is large, and the instantaneous large amount of lost will result in the completely lost. The second layer, small dissolved pores are developed, and the inclined and horizontal fractures are growth, but are fully or partial filled. The third layer, Karst caves and fractures are developed, pores are extremely developed, and reservoir features are the most complex. Therefore, the main type of lost circulation mechanism on the Amu Darya is the fracture-cavity leakage, which accompanied by expansive lost [4-7].

Figure 1. Characteristics of reservoir fractures in Amu Darya River.
The severely lost horizons in the Halfaya oilfield are mainly concentrated in the fractures and karst caves developed in Jaddala layer - Mishrif layer, as shown in Figure 2.[8] The fractures of Jaddala and Aliji layers are mainly developed by induced fractures [9]. The formation bearing pressure capacity is poor which is easy to induce fractures, leading to the loss of drilling fluid result in a fracturing loss. Shiranish layer fractures and pores are developed and there are karst caves. Due to the development of fractures and pores, it is easy to cause leakage. Fractures and pores growth are mainly in the Mishrif layer, where the formation pressure is gradually reduce with the development of the oil field, the frequent lost is induced by the imbalanced formation pressure. The lost or partial lost problems in Nahr UmrB layer and the Yamama layer are relatively easy to control.[10] As analysed, the types of loss mechanisms in Halfaya Oilfield are mainly fracture loss and fracture-cavity loss.

![Figure 2. Characteristics of reservoir fractures in Halfaya.](image)

3. **Flowing and plugging model establishment**

Figure 3 is the Physical Model of Horizontal V Funnel Lost Channel, which stimulates the flow channel of particles containing plugging liquid material. The front and rear boundaries conditions are set as periodic condition, and up and down boundaries are fixed physical boundaries. The right side boundary is set as velocity boundary, where fluid and particles flow into the channel with the same inflow velocity (1.2L/s), and a constant inflow condition is stimulated for the process of particle-containing plugging liquid flow. The bottom boundary is the free outflow boundary condition, where the fluid density is 2200kg/m³, the yield stress is 13.5Pa, and the plastic viscosity is 1.8pa.s. The normal and tangential stiffness of the particles are \(k_n=5\times10^5\) N/m and \(k_t=1\times10^5\)N/m, respectively, and the damping ratio is \(c_n=c_t=0.5\). Unless otherwise specified, these mentioned parameters were carried out in the simulation. In the simulation, the flowing path diameter is changed by changing the size and diameter of the gap, and the flow and plugging regime of particles containing liquid in the channel are observed. The variation of particle volume fraction is studied through statistic of the particle flow and fluid flow through the channel. Noted, the outflow of the containing particles liquid to plug the loss should be less than the inflow when the channel is relatively narrow. As a result, the particles will accumulate above the gap, and filling the entire channel. When the channel is fully filled, the newly input particles at the entrance will overlap with the previous particles, causing the calculation to collapse and fail to obtain a stable flow state. In order to obtain a stable flow, the input flow rate is restricted when the particles fill the 3/4 channel, so that the input flow rate is equal to the output flow rate. A particle flows out at the outlet, while a particle is input at the inlet.

![Figure 3. Horizontal V funnel lost channel model.](image)

The simulation results are recorded with experimental observation and analysis. The test process could be recorded by camera. First, the V funnel was filled with water, then drop in a drop of ink to increase the contrast between the water and the transparent plexiglass to make the observation results...
clearer. After the ink is evenly mixed, turn on the switch at the bottom of the V funnel, and the water flows out quickly from the funnel. The whole falling process is recorded by the camera.

At the beginning of the simulation, the Bingham fluid-particle two-phase flow is input from above the channel to represent the flow process of the particle-containing plugging liquid. The particles are randomly distributed, and the particle-containing plugging liquid quickly filled the entire channel and form a stable flow. The diameter of the large particles (gap) is gradually increased, so that the aperture ratio $D$ decreases from 7.2 to 1.2, and the flow regime of the containing the particle plugging liquid is observe as Figure 4. The flow regime acts as 3 flow patterns: sparse flow, dense flow and plugging, which is similar to dry particle flow. When $D \geq 2.0$, the size of the channel formed by the gap is larger than the diameter of the plugging liquid. The input plugging liquid containing particles can pass through smoothly, and will not be accumulated above the gap, nor will the plugging of the occur. The output flow is equal to the input flow therefore the sparse flow is formed. The size of the channel is relatively small When $D \leq 1.8$. The particles are accumulated above the gap, and the channel is partially plugged.

Although there is stable outflow, the outflow rate is less than the inflow rate due to the particles accumulation. The dense flow is formed. When $D=1.2$, the size of the channel is slightly larger than a particle diameter, the plugging fluid could hardly pass through the channel. 0 outflow is observed and plugging regime is achieved.

When the outflow is stable, the particle flow rate and fluid flow rate through the gap are observed as Figure 4 showed. The particle flow rate and fluid flow rate varied with the different aperture ratio. For the sparse flow with $D>1.9$, the flow rate of particle flow out of the gap is the same as the input flow rate. The output flow is equal to the input flow, which does not change with the change of the aperture ratio. When dense flow is achieved with $1.3< D<1.9$, the flow rate of particle flow out of the gap is smaller than the input flow rate, which declines with the decreasing aperture ratio. When $D \leq 1.3$, the channel is fully blocked. There is a clear critical transition point between these three regimes. When the pore size is relatively large, the flow is relatively smooth, the particles move under the fluid, and they hardly interact with other particles and the side walls. The input particles can smoothly pass through the channel, so the output flow is equal to the input flow. However when the pore size is small, the particles accumulate above the gap to form a stable structure. The main role is the contact between the particles and the particles and the gap. The rate of the particles accumulation is almost 0, and the outflow rate is mainly determined by the size of the channel. When the aperture ratio is further reduced, the accumulated particles are very easy to form a stable arch structure, so that the flow of particles stops completely.
The fluid flow rate decreases with the decreasing aperture ratio, and the variation is relatively slow, as Figure 5 showed. When $D>3.2$, fluid flow rate is smooth. However, when $1.9<D<3.2$, the declination is serve. When $D<1.9$, almost 0 fluid rate is reached comparing to when aperture is large. The flow of fluid in the channel is not only influenced by gravity, but also hindered by the surrounding walls and fixed large particles, as well as by moving particles. When $D>3.2$, the contraction of the channel is not obvious, so the change in fluid flow is relatively smooth. The fluid flow rate change significantly caused by the contraction of the channel, while the fluid flow decreases sharply as the aperture ratio decreases ($1.9<D<3.2$). When $D<1.9$, the movement of particles changed from sparse flow to dense flow, and the particles accumulated above the gap, forming a densely arranged porous medium, resulting in a sharp decrease in the porosity. The densely packed particles not only reduce the fluid flow rate, but also increase its flow resistance, making the flow of the fluid more difficult, so the flow rate of the fluid is further reduced to almost zero.

The changing rules of fluid flow rate and the particles flow rate with the changing aperture ratio are different, which will change the particle content of the plugging materials passing through the channel. As shown in Figure 6, the particle content of the plugging material has changed greatly with the change of the aperture ratio. When $D>3.2$, the particle content remains basically unchanged, and both fluid and particles can smoothly pass through the channel. When $1.9<D<3.2$, The particle content increases rapidly (approaches 1), the flow rate of particles flowing through the channel remains almost unchanged, but the fluid flow rate is greatly reduced. The rate of particle content increases rapidly. The rate of particle content is almost 1 when $D<1.9$, as a result, less fluid flows through the channel. Although the particles can pass steadily at this time, there is less fluid passing through the channel, meaning that the content of liquid particles of plugging material increases sharply, which easily leads to subsequent flow blockage.

In summary, the aperture ratio is the most important factor that determines the flow and plugging of the liquid plugging material. The larger the aperture ratio is, the smoother the flow of the particles containing plugging liquid. The channel is more likely to be partially or fully plugged with the particles containing plugging liquid when the aperture ratio is small.

4. The development of responsive plugging material for carbonate reservoir

The combination of the main plugging materials, suspending agent, filter aid and curing agent are optimized. The characteristics of each component are comprehensively considered. It requires the plugging agent to have faster water loss, mass water loss, good stability, high filter cake strength, and high acid dissolution rate. Two responsive controllable curing high water loss plugging materials have been developed: 60%-80% main material, 8%-12% suspending agent, 8%-10% curing agent, 5%-10% filtration aid Agent.

- Plugging material A formula: 40%ZT-2+30%ZT-4+12%XFJ-2+8%GHJ-3+10% Filter aid
- Plugging material B formula: 50%ZT-2+20%ZT-4+12%XFJ-2+9%GHJ-3+9% Filter aid
4.1. Testing of mud cake strength

Regular filter cake is formed with the plugging material. The compressive strength and compressive strength of the filter cake is tested with a uniform loading pressure testing machine. The testing results are shown in Table 1. Sample A has a lower compressive strength than sample B which is due to the high content of ZT-2 in sample B. The strength of ZT-2 after curing is extremely high, and it shows better toughness under the action of suspending agent reinforcement. It is more suitable for plugging operation under higher pressure capacity requirements. The compressive strength of samples A and B exceeds 7MPa, which could meet the demands of downhole plugging operations.

![Particle Content Under Different Aperture Ratio](image)

**Figure 6.** The particle content under different aperture ratio.

| Sample  | Compressive Strength KN | Compressive Rating MPa |
|---------|-------------------------|------------------------|
| Sample A | 17                      | 7.16                   |
| Sample B | 17                      | 8.12                   |

4.2. Testing of acid dissolution rate

The sample A and B are weighted separately, and then be added to hydrochloric acid (10%) with a mass of 2m, 4m, 6m, 8m, and 10m. The sample dissolves rapidly in hydrochloric acid. Figure 7 demonstrates the acid dissolution rate under different mass fractions in hydrochloric acid. The experimental results show that as the amount of hydrochloric acid added increases, the acid dissolution rate gradually increases. The acid dissolution rate of the sample reaches the maximum when the amount of hydrochloric acid added is 6 times the mass of the sample. The acid dissolution rate of sample A is 91%, and the acid solubility of sample B is 87%. Since the main material ZT-4 is almost completely acid soluble, the content of ZT-4 in sample A is high, sample A shows better acid solubility and is more suitable for reservoir plugging.

4.3. HPHT filtration test

In order to further explore the water filtration performance of the plugging agent under high temperature and high pressure, the filtration and filtration period is measured with A high temperature and high pressure water loss meter. The composition of the experimental plugging slurry is: fresh water + 20% of sample B. The plugging slurry volume is 350ml. The experimental conditions are: upstream pressure 4.2 MPa, downstream pressure 0.7 MPa, pressure difference 3.5 MPa. The experimental results are shown in Figure 7. The filtration loss is basically completed in approximately 60s, and the filtration loss
tends to decrease as the temperature increases, but the overall performance is stable. It is further proved that the curable high filtration loss plugging material has 150℃ high temperature resistant in fresh water, as shown in Figure 8, and the plugging strength of the solidified plug can reach more than 10 MPa and is stable for 15 days, showed in Figure 9, which could meet the onsite construction requirements of the long open hole section.

![Figure 7. Plugging material acid dissolution rate with hydrochloric acid mass.](image)

![Figure 8. Filtration loss performance with temperature.](image)

![Figure 9. Curing strength curve.](image)

5. Conclusion
1. The main type of lost circulation mechanism on the Amu Darya is fracture-cavity leakage, accompanied by expansive losts, and the types of loss mechanisms in the Halfaya Oilfield are mainly fracturing loss and fracture-cavity loss.

2. The aperture ratio is the most important factor that determines the flow and plugging performance of the liquid plugging material. The larger the aperture ratio, the smoother the flow of the particles containing plugging liquid. The channel is more likely to be partially or fully plugged with the particles containing plugging liquid when the aperture ratio is small.

3. The dissolution rate of the responsive well plugging material is up to 91%, the plugging strength of the solidified plug is up to 10MPa and it has the ability to be stable for 15 days under 150℃.

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