Experimental Study on Stimulation of Horizontal Wells Filled with Film-Coated Gravel in Deep-Sea Bottom-Water Gas Reservoirs

Jiqiang Zhi, Rongzhou Zhang,* Guohui Qu, and Nan Jiang

ABSTRACT: Large gas reservoirs such as Yacheng and Lingshen have been discovered in the exploration of deep-sea gas reservoirs in the South China Sea in recent years. However, the existence of bottom-water and sufficient water energy in deep-sea gas reservoirs seriously affects the development effect of gas reservoirs. In order to effectively control water development of deep-seabed water gas reservoirs, it is proposed to fill water-resistant and breathable coated gravel outside horizontal wells for mining. Based on the preparation of modified coated gravel, this paper studies the resistance of coated gravel to friction damage, temperature damage, acid damage, pressure damage, and water-resistant performance of coated gravel. The results show that (1) the coated gravel coating has good resistance to friction erosion and acidification corrosion. The upper limit of temperature resistance is 250°C, and the pressure resistance is 90.4 MPa. (2) The water resistance of the film-coated gravel packing layer decreases with the increase of packing layer permeability. (3) The film-coated gravel pack can reduce the water-phase flow ability of reservoirs, delay the bottom water ridging speed, increase the waterless gas development time of gas wells, and improve the final recovery of bottom-water gas reservoirs. The coated gravel has permeability and water resistance properties and can be used to voluntarily select water plugging in the coated gravel pack. This technology can develop a new technical idea for water control of deep-seabed water gas reservoirs.

1. INTRODUCTION

Since 2014, large deep-sea gas reservoirs such as Yacheng and Lingshen have been discovered in the South China Sea. Among them, the Lingshen 17-2 gas field (core gas field) has a water depth of 1250–1500 m, a buried depth of 3200–3500 m, a permeability between 92 and 2563 mD, with an average permeability of 552 mD, and an average porosity of 30.4%. The formation pressure is 37.6–40.1 MPa; the formation temperature is 85.3–92.8°C; the reservoir is high-temperature and high-pressure, high-porosity, and high-permeability sandstone reservoir; and the geological reserve is 1031.26 × 108 m3. The gas reservoir has a large area of bottom water with sufficient energy. The distance between the bottom water and the middle of the producing layer is 35 m, and the risk of bottom-water invasion is high. In the development process of deep-sea (water depth > 1000 m) unconsolidated sandstone bottom-water gas reservoirs, it is difficult to implement the water control technology because of insufficient reservoir understanding. In the deep sea area, the working conditions are complex, and it is difficult to use and maintain the water control tool and the cost is high. Once the downhole water control tool has problems, it is difficult to continue the production of the gas production well. As a result, effective water control is very important for deep-sea bottom-water gas reservoir development. Mechanical blocking, chemical plugging, ICD, AICD, variable density screen pipe, and other water control technologies all require a fine description of the reservoir and are both expensive and difficult to implement. In addition, the ICD and AICD water control equipment are blocked by sand particles due to the easy sand production in loose sandstone gas reservoirs. The gravel packing sand control technology cannot be implemented due to the difficulty of well completion and high operation cost due to
the central control water technology. Moreover, the central control water technology is not suitable for water control in heterogeneous reservoirs, and the bottom water ridge cannot be balanced.7 Based on the gas well water control technology and the efficiency and practicability of the two into consideration, we put forward the use of the preparation of the modified effect of gravel in bottom-water control research on the effect of gravel rubbing damaged, broken temperature resistance, acid resistance, resistance to fill breakage, the coated layer of gravel block water ability test, and then, we used a large three-dimensional bottom-water reservoir development simulator experiment and compared and analyzed the development effect of horizontal well packing conventional gravel and coated gravel.

2. EXPERIMENTAL SECTION

2.1. Preparation Process of Coated Gravel. Epoxy resin (4000 mL) was dissolved in ethyl acetate solution (6000 mL); the volume ratio (the material volume and the volume ratio of epoxy resin, hereinafter the same), 25% soluble poly(tetrafluoroethylene), in order to construct a microhydrophobic–nanohydrophobic structure, and hydrophobic silica nanoparticles (the volume ratio is 3%; the average particle size is 40 m) were added; and conventional gravel particles (40% by volume) were added. In order to increase the damage resistance of the coated gravel coating, 19% polyurethane powder was added to the mixture after ultrasonic agitation for 1.2 h, followed by ultrasonic agitation for 20 min and microvibration for 3 h in a 90 °C air blowing drying oven to prepare T-I type coated gravel particles8−10 (Figure 1).

![Coated gravel](Figure 1. Coated gravel.)

2.2. Simulation Experiment Process of Large Bottom-Water Gas Reservoir Development. The experimental device is shown in Figure 2. The length, width, and height inside the axe body are 500 mm. Film-coated gravel was filled inside the axe body, and the permeability was adjusted to 1500 mD by compaction. A total of 30 groups of electrode probes were arranged in the corresponding positions inside the kettle body, with 5 electrodes in each group and a total of 150 test points. By testing the variation of the water saturation field of the bottom-water drive gas reservoir under different exploitation conditions, furthermore, the water-blocking and stimulation effect of the film-coated gravel pack was evaluated.11 Based on A1H gas well parameters, the range of the gas reservoir is 3200 × 1100 m, and the average porosity is 0.304. The horizontal section of A1H is 300 m, and the distance from bottom water is 60 m. The daily gas production of the gas well is 100 × 10⁴ m³. In the physical simulation experiment of the bottom-water gas reservoir, a 30 cm wellbore was selected to simulate the horizontal section of the gas well, 30 cm from the bottom-water wellbore. According to the similarity criterion,12 the displacement pressure difference was determined as 0.4 MPa and the gas production was 586.4 mL/min. The experimental steps are as follows: (1) the corresponding horizontal shaft (diameter: 6 mm, hole density: 4 holes/cm) is arranged in the kettle body, and then the axe body is filled with quartz sand (the horizontal shaft is surrounded by a gravel pack with a thickness of 4 cm). The bottom water separator is arranged at the bottom of the kettle body. (2) Water is injected into the kettle body through valve 4, the pore volume of the gas reservoir model is 32.4 L, injected gas is injected by valves 1 and 2 and flows out by valves 3 and 4, irreducible water saturation of the gas reservoir model is 0.23, and then valve 4 is opened until the bottom aquifer is full with injection water, at which point all valves are closed. (3) From valve 2 gas is injected, and when the internal pressure of axe reaches 10 MPa the air injection is ended. (4) The physical simulation experiment of bottom-water pressure displacement gas recovery is carried out, and the gas production and water production of the model are recorded. The experiment is finished when the water cut at the produced end reaches 98%. Through the signal data recorded by the electrode probe at different times, the bottom-water inflow of the gas reservoir model at different times is obtained by software inversion.

3. RESULTS AND DISCUSSION

3.1. Performance Test of Coated Gravel. 3.1.1. Filling Damage Resistance Test. Due to the wear between gravel particles and the borehole wall, and the reservoir rock and particles during the filling process of coated gravel, it is necessary to conduct an experimental test on the filling wear resistance of coated gravel to determine the damage resistance safety limit of coated gravel. Since the indoor experiment cannot simulate the filling process of coated gravel in the reservoir under the conditions of a long distance, high temperature, and high pressure (Figure 3), according to the principle of distance equivalence, this paper carries out experimental simulation research through the circulating flow mode of coated gravel in the local short distance (the temperature and pressure are consistent with reservoir conditions) (Figure 4).

Experimental steps: (1) according to the proportion of 40% by volume of coated gravel, T-I coated gravel is added into a clean sand-carrying liquid with a viscosity of 4 mPa·s. (2) The prepared solution is put into the high-temperature and high-pressure rotating device. The inner diameter of the device is 0.3 m, and the distance from the inner wall to the outer wall of the device is 0.15 m. According to the reservoir conditions of deep-seabed water and the gas reservoir in the South China Sea, the device temperature is set to 90 °C, the pressure is set to 40 MPa, the gravel packing speed in the open hole section of well a1h in the South China Sea is 0.6 m/s, and the packing speed of the indoor device equipment is 40 rpm. The experimental filling speed is set at 40 rpm (0.6 m/s), 160 rpm (2.4 m/s), and 320 rpm (4.8 m/s). The experiment is stopped when the coated gravel flows for 1800 m (6 times the length of the horizontal well section) in the experimental device and equipment. (3) The coated gravel is taken out from the experimental equipment and filtered (90 mesh screen) and dried. (4) The surface morphology changes of T-I coated gravel before and after packing were observed using a field emission projection electron microscope (Tecnai G2 F20 S-TWIN).

Figure 5a shows the microstructure of the coated gravel under the original conditions. The surface presents a white dot-like material and a concave–convex mechanism. The white dot-like...
material has a microhydrophobic−nanohydrophobic structure. The enlarged microstructure is shown in Figure 5b. The contact angle of the coated gravel under the original conditions is 162°; under the reservoir filling conditions (the filling speed is 0.6 m/s, and the temperature is 90 °C), the surface hydrophobic structure of the coated gravel changes little and is basically not damaged. The contact angle of the coated gravel is 156°; when the filling speed gradually increases (Figure 5c−e), the surface wear degree of coated gravel increases, but there is still a microhydrophobic−nanohydrophobic structure, and the contact angle of coated gravel is still greater than 146°.

3.1.2. Temperature Damage Test. In order to test the hydrophobic performance of coated gravel at high temperature, the coated gravel was placed in a high-temperature incubator, and the temperature distribution was set at 200, 250, and 300 °C. After standing for 30 days, the surface microcoating state of coated gravel was observed using the field emission projection electron microscope (Tecnai G2 F20 S-TWIN).

When the temperature is 200 °C, the coating structure of coated gravel surface is stable (Figure 5f), and the contact angle of coated gravel is greater than 143°; when the temperature is 250 °C, the coating structure on the surface of coated gravel begins to damage (Figure 5g), and the contact angle of coated gravel decreases to 76°; when the temperature is 300 °C, the coating structure on the coated gravel surface is completely broken (Figure 5h), and the contact angle between the coated gravel layer and the coated gravel is close to 0°, and the hydrophobic function is lost, mainly because the covalent bond

Figure 2. Schematic diagram of the simulation device for development of a large bottom-water gas reservoir: (a) connection flow chart of experimental equipment, (b) front view of the main kettle body, and (c) physical drawing of the experimental device.

Figure 3. Schematic diagram of the gravel packing technology in the horizontal well.

Figure 4. Schematic diagram of the gravel friction damage testing device.
between the amine group of the coated gravel coating and the epoxy group of the epoxy resin is destroyed by the high temperature of 300 °C (Figure 6).

3.1.3. Acid Damage Test. The molar content of CO₂ in the natural gas components of the LS 17-2 block ranges from 0.2 to 0.7526%, and the pH value measured after dissolving in water ranges from 3.5 to 6.4. The coated gravel is placed in a carbonated solution with a pH value of 3.0, and it is put in a thermostatic oven with a temperature of 90 °C. The samples were taken out at intervals, and the coating morphology was observed by scanning electron microscopy and magnified to 1600 times, as shown in Figure 7. The results showed that with the increase of test time, the surface morphology of the coated gravel coating is slightly corroded, but the corrosion damage degree is less than 2% after soaking in an acid for 10 months.

3.1.4. Pressure Damage Test. The water-resistance ability of film-coated gravel depends on the superhydrophobic property of gravel surface coating. The gravel packing of horizontal wells in deep-sea gas reservoirs has a high-intensity filling and compaction effects under the special working conditions. It is necessary to conduct relevant mechanical tests to determine whether the packing-resistance strength of film-coated gravel surface coating is reliable. A particle strength tester was used to measure the compressive strength of coated gravel layers with different cross-sectional area combinations. The test scheme and results are shown in Table 1: casing 9-5/8 in., a gravel pack thickness of 4 cm, and a calculated gravel pack cross-sectional area around the horizontal well of about 0.00155 m². From the experimental test data regression cross-sectional area and the upper limit of pressure of coating damage (as shown in Figure 8), it was calculated that the limit of pressure damage that the cross-sectional area of gravel wrap can withstand is 90.4 MPa, which is much higher than the formation fracture pressure and is safe and reliable.

3.2. Water Resistance Test of Coated Gravel. A layer of conventional gravel particles and T-I-type coated gravel particles
with a thickness of 0.5 cm and 40 mesh were laid on the desktop under atmospheric pressure visible conditions, and then, the dripping experiment was conducted. As shown in Figure 9, water droplets gather on the surface of the coated gravel layer in a spherical shape, while on the surface of the conventional gravel layer, water droplets penetrate into the gravel layer. The experiment shows that the T-I-coated gravel has good water blocking effects and hydrophobic characteristics. The contact angle of the coated gravel layer is greater than 90°, and the

![Figure 7](image_url)  
Figure 7. Test results of acid resistance of gravel surface coating: (a) original topography, (b) 2 months, (c) 4 months, (d) 6 months, (e) 8 months, and (f) 10 months.

### Table 1. Experimental Scheme and Test Results

| area (10⁻⁸ m²) | grain number | compressive strength (KN) | group number | average compressive strength (KN) |
|---------------|--------------|---------------------------|--------------|----------------------------------|
| 5             | 1            | 0.8                       | 3.1          | 2.8                              | 1.9                              | 2.3                              | 2.18                             |
| 25            | 5            | 14.7                      | 9.6          | 10.1                             | 11.4                             | 11.8                             | 11.52                            |
| 50            | 10           | 15.1                      | 30.5         | 19.4                             | 23.8                             | 24.5                             | 22.66                            |
| 250           | 50           | 105.5                     | 130.8        | 95.2                             | 130.4                            | 114.7                            | 115.32                           |
| 500           | 100          | 231.8                     | 226.1        | 233.3                            | 226.6                            | 232.4                            | 230.04                           |
| 750           | 150          | 343.4                     | 371.3        | 360.5                            | 383.7                            | 375.5                            | 366.88                           |

![Figure 8](image_url)  
Figure 8. Relationship between cross-sectional area and compressive strength of the coated gravel pack.

![Figure 9](image_url)  
Figure 9. Water dripping experiment of gravel layers.
capillary force becomes the blocking force. Because the gravity of the water droplets is less than the capillary force, water droplets cannot penetrate into the coated gravel layer and remain on its surface. The conventional gravel layer has good hydrophilicity and no water blocking performance, and water droplets invade the conventional gravel layer.

In order to quantitatively describe the water resistance of gravel, it is necessary to test the water resistance of backfill. The experimental device is shown in Figure 10, and the experimental steps are as follows: (1) as the actual gravel pack thickness in the horizontal well section of A1H ranges from 2.54 to 5.08 cm, the thickness of the gravel layer is 4 cm when the conventional gravel (40 mesh) is packed into the sand filling pipe. (2) Constant pressure gas injection is carried out, and the filling method is adjusted continuously until the gas permeability of the filling layer is 1500 mD after the gas output is stabilized and recorded. (3) The water injection experiment was carried out under the condition of constant pressure, and the water production rate of different displacement pressure differences in the filling layer was recorded; (4) T-I-type coated gravel (40 mesh) was reinserted into the sand filling pipe. The thickness of the coated gravel layer is 4 cm, and gas injection and water injection experiments were conducted [experimental steps (2) and (3)]. On this basis, according to the conventional gravel and coated gravel packing layer gas permeabilities of 100, 200, 500, 1000, and 2500 mD, the water resistance performances of the backfill layer test were analyzed; the gas−water two-phase relative permeability curves of the conventional gravel packing layer and the film-coated gravel packing layer are tested, and the permeability of the packing layer is 1500 mD; see GB/T28912-2012 for the specific test method.

Formula 1 is used to calculate the water-resisting capacity (δ) of the packing layer

\[
\delta = \frac{Q_{wi} - Q_{wT-I}}{Q_{wi}}
\]

Here, \(Q_{wi}\) represents the water production rate of the conventional gravel layer, mL/min, and \(Q_{wT-I}\) represents the water production rate of the coated gravel layer, mL/min.

As shown in Figure 11a, with the increase of filling speed, the water resistance of the coated gravel layer decreases slightly, but it still has strong water resistance. When the temperature reaches 200 °C, the water resistance of the coated gravel layer is strong, and the microhydrophobic−nanohydrophobic structure of the coated gravel surface is stable. When the temperature is 250 °C, the microhydrophobic−nanohydrophobic structure of the coating on the coated gravel begins to get damaged and the water resistance decreases obviously. When the temperature exceeds 300 °C, the damage of the coating on the surface of the coated gravel is serious and the water resistance is lost. It can be seen that temperature is an important factor affecting water resistance of the coated gravel layer, and the critical point of temperature for T-I-type coated gravel is 250 °C.

It can be seen from the water resistance test of the coated gravel pack under different permeability conditions (Figure 11b) that the water resistance of backfill decreases with the increase of permeability. When the displacement pressure difference is 0.4 MPa, the water-resisting capacity of the 100 mD gravel pack decreases to 0.54, while that of the 2500 mD gravel pack decreases to 0.167. When the permeability of the coated gravel pack ranges from 100 to 1500 mD and the displacement pressure difference is from 0.1 to 0.6 MPa, the water resistance of coated gravel ranges from 0.21 to 0.73. At a filling thickness of 4 cm, the gas drive water displacement differential pressure is 0.4 MPa and the filling layer permeability

![Figure 10. Schematic diagram of the gravel pack water resistance test device.](image)

![Figure 11. Relationship between water-blocking capacity of the gravel pack and displacement pressure difference: (a) different working conditions and (b) different permeability conditions.](image)
is 1500 mD; under these conditions, testing conventional gravel and effects of the gravel layer of the gas–water relative permeability curve, as shown in Figure 12, the gas–water-phase permeability curve of the coated gravel pack moves downward, and the isopermeability point and right end point
move right, with a two-phase seepage zone width. This shows that the laminated gravel pack has obvious water resistance.

3.3. Laboratory Physical Simulation Experiment of the Bottom-Water Gas Reservoir. The simulation experiment of the bottom-water gas reservoir is shown in Section 2.2. With conventional gravel filling in the horizontal interval and bottom-water cresting development characteristics as shown in Figure 13, the production end moisture content was 98%, there was uneven distribution of water saturation in the horizontal interval and a horizontal section heel into a clear water invasion ridge, the heel apparent above is the toe water saturation, water saturation is mainly due to the premature nature to see the water in the horizontal interval, water is serious, the pore volume of residual gas in the gas reservoir is 34.56%, and a large amount of gas is still trapped in the gas reservoir. The effect of gravel filling in the horizontal interval and bottom-water cresting development characteristics are shown in Figure 14, which shows that compared with the conventional gravel mining, there was uniform water saturation distribution along the horizontal section, the horizontal section water invasion ridges into different positions close to the horizontal well with water saturation and toe water saturation were similar, the mixing effect was good, and the remaining gas pore volume was 30.14%. Through different times of the bottom-water cresting diagram (Figures 15 and 16), it can be seen that when the bottom water reaches the gravel layer, because the effect of gravel has water resistance ability, it can slow the flow of water in the gas phase, delay the bottom water into the horizontal section, extend the time of wellbore waterless gas extraction, achieve the effect of water control in bottom-water reservoir development, and improve the gas reservoir recovery efficiency.

A comparative analysis was made on the simulation experiment of bottom-water ridge filling with conventional gravel and coated gravel in the horizontal well section. The experimental production data are shown in Figure 17. Once water is produced from the wellbore filled with conventional gravel in the horizontal well section, the daily gas volume decreases rapidly, the daily water volume increases rapidly, and the recovery factor is low. However, when the film-coated gravel is used to fill the horizontal well section, the daily gas volume decreases slowly, the daily water volume rises slowly, the gas well recovery time is long, and the recovery factor is increased by 5.83%.

4. CONCLUSIONS

(1) The upper limits of temperature and pressure of coated gravel are 250° and 90.4 MPa, respectively. The coated gravel coating has good resistance to friction erosion and acidification corrosion. When the filling speed is 4.8 m/s, the microhydrophobic/nanohydrophobic structure of the surface coating remains intact and the water resistance is good. After soaking in an acid for 10 months, the corrosion damage is less than 2%.

(2) With the increase of permeability, water resistance decreases. When the permeability of the coated gravel pack ranges from 100 to 1500 mD and the displacement pressure difference is from 0.1 to 0.6 MPa, the water resistance of coated gravel ranges from 0.21 to 0.73.

(3) Film-coated gravel pack can reduce the water-phase flow ability of the reservoir, delay the bottom-water ridging speed, increase the waterless gas development time of the gas well, and improve the final recovery of the bottom-water gas reservoir.

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Figure 16. Horizontal well bottom-water front ridge entry profile: (a) bottom water does not reach the gravel layer, (b) water ridge in front of the gravel layer, and (c) gas drive end stage.

Figure 17. Yield relationship between the gravel pack and conventional gravel.
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Notes
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