Macro- and Microanalysis on Noncondensable Gas Antiwater Invasion in a Bottom Water Reservoir with a Rupturable Interlayer

Zhanxi Pang,* Jiajie Chen, Dong Liu, and Yuhao Zhou

ABSTRACT: Developing a bottom-water reservoir with rupturable interlayers is a significant challenge. This paper used a 2D visualization model to study the seepage characteristics of gas–water in two phases during noncondensable gas antiwater invasion. On this basis, the mechanisms of antiwater invasion and enhanced oil recovery (EOR) were summarized. The results show that bottom water advances from the crack of the interlayer to the oil layer, leading to a profile of radial flow. The major swept area occupies the scope near the horizontal well and the oil layer’s middle part. Therefore, a lot of remaining oil distributes beside the crack of the interlayer. Noncondensable gas preferentially flows into the water-swept area due to a lower seepage resistance. Under gravity differentiation, the dispersed gas displaces the invaded bottom water downward, inhibiting water from invading and increasing the oil production rate. These studies provide practical guidance for analyzing bottom-water invading processes and designing suitable measures to develop such reservoirs.

1. INTRODUCTION

Bottom water reservoirs are widely distributed worldwide, with a primary characteristic of oil and water layers coexisting. During an early production period, bottom water can play a role in complementing formation energy. During an early production period, bottom water can play a role in complementing formation energy. Once the product enters the middle or late stage, severe water invasion will cause many problems, such as a shortage period of water-free oil production, a rapid rise in water cut, even violent water invading and increasing the oil production rate. These problems directly affect the production efficiency in the oilfield. Bottom water invasion is the key to restricting the effective development of bottom-water reservoirs.

However, if water invasion is governed reasonably and strategically, the active bottom aquifer will be a positive energy source for enhancing oil recovery. Horizontal wells have been widely used in bottom-water reservoirs, effectively increasing oil production and decreasing water invasion. Compared with vertical wells, horizontal wells can effectively postpone the emergence of water coning. However, bottom water gradually invades the oil zone and eventually moves toward the wells, which still is a significant problem in bottom-water reservoirs. Although the bottom aquifer can complement the deficit of formation energy, bottom-water breakthrough will cause a sharp drop in oil production and even lead to the abandonment of horizontal wells. The results are from the imbalance of gravitational and viscous forces. Therefore, there are two main problems involving horizontal wells in bottom-water reservoirs: one is to effectively decrease the bottom water’s advancing speed and prolong the water-free oil production period, and the other is to control the degree of water invasion and to realize a high oil recovery factor.

The injection of selective plugging agents is one of the crucial methods for profile control and water shutoff in oil fields. To effectively decrease water invasion and improve the production efficiency in bottom-water reservoirs, various measures, such as gas injection, foam injection, weak gel plugging, and solid particle plugging, have been applied widely. Although a particular effect has been achieved, field application still has some difficulties, such as poor foam stability, short validity period, and uncertain plugging outcome. The profile control used gel agents to increase oil production to a certain degree; however, the water cut does not decrease significantly. Conventional solid particles are prone to premature failure under the conditions of high temperature and a short residence time. Injection of cold, noncondensable gas with associated additives into producers to achieve the purpose of decreasing water invasion, developed by Alberta Oil Sands Technology Research Authority (AOSTRA), was patented in 1985 as Anti Water Coning Technology (AWACT). Noncondensable gas injection into an oil
reservoir with bottom water has been observed as an effective antiwater invasion method to extend a production well’s economic life.\cite{31,34} It has been found that nitrogen has good expansibility and compressibility, which can effectively supply the formation energy. Compared with other measures, nitrogen injection is the most economical and rational method because nitrogen, as an inert gas, is a major component of air. In addition, this technology has been verified in field applications to effectively reduce water cut and increase oil production.\cite{35,36}

There are many bottom-water reservoirs with thin rupturable interlayers whose thickness is less than 1m. For this kind of reservoir, nitrogen injection is a selectable method to resist water invasion from the broken interlayer to the horizontal production well. Multiphase flow is one of oil and gas production activities’ most common and complex problems. In the nitrogen injection process in bottom-water reservoirs, the flow description of multiphase flow is crucial. Recently, with the global popularity of artificial intelligence, advanced methods such as deep learning and machine learning have been increasingly applied to the dynamic process description of phase equilibrium, simulating multiphase flow in subsurface multiphase media that is more accurate and reliable.\cite{37,38} In this article, according to the analysis of two gas–water phases, a series of 2D visualization experiments were used to simulate the production performance of a horizontal well and then to analyze the distribution characteristics of the gas phase in the oil or water layer. At last, the mechanisms of antiwater invasion and enhancing oil recovery were summarized in the bottom-water reservoir during nitrogen injection. As a result, it is essential to explore effective antiwater swarming technology and to provide a basic understanding of production strategies and adjustment measures for bottom-water reservoirs.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

2.1. Experimental Conditions. This article used the white oil of 46° as an experimental oil sample, with a dynamic viscosity of about 40 mPa·s. The observed water sample was configured according to the component analysis of formation water in an actual reservoir in China. Formation water belongs to the type of sodium bicarbonate, whose total salinity is 9051 mg/L. An electric heating device was installed outside the injector’s inlet and along the pipelines. During the experiments, the device’s temperature is consistent with the whole system, so the injected fluids such as formation water and nitrogen are kept at the same temperature inside the model.

2.2. 2D Visualization Experiment. A series of 2D visualization experiments were conducted to analyze the mechanisms of nitrogen antiwater invasion from bottom water to a horizontal well. As shown in Figure 1, the 2D visualization experimental apparatus mainly consists of five parts: an injection system, model system, production system, acquisition system, and auxiliary system. The injection system comprised pumps, nitrogen cylinders, gas mass flow meter, etc. The model system mainly included a 2D visualization model, a constant temperature oven, etc. The production system was mainly composed of volumetric cylinders and hand pumps. The acquisition system consisted of a high digital camera, a data acquisition device, and a display, and the auxiliary system was composed of pressure gauges and control valves. The camera was placed directly in front of the 2D visualization model to obtain real-time distribution characteristics of fluids on a macro- or microscale. The flux of nitrogen injection was regulated by a gas mass flow meter, and an injection pump controlled the change of liquid injection. A data acquisition system was used to record the data on temperature and pressure in real time. In real time, the volumetric cylinders were employed to accurately measure and collect the oil and water production volume at the outlet. The 2D visualization model is illustrated in Figure 2. The model was assembled with two pieces of quartz glass with a thickness of 3 cm. The visible inner length or width was 20 cm in the model, which was filled with 40-mesh glass beads to form a transparent porous media. The inner thickness was only about 1.2 mm in the model.

According to the actual reservoir’s geological parameters, the net pay is nearly 10m, and the interlayer thickness is about 2m. The absolute permeability is about 2 μm², and the porosity is about 34%. Therefore, the experimental design was completed according to the similarity criterion of water flooding. The 2D model is shown in Figure 2. A horizontal well was arranged at the top of the 2D model. The length of the horizontal well was 20 cm in the experiment, which corresponds to 20m (equivalent to 1/10 of the actual length) for the horizontal well in the existing reservoir. The thickness of the oil layer was 10 cm in the experiment, which corresponded to 10m for the net pay in the actual reservoir. The thickness of the interlayer was 2 cm, reaching 2m for the thickness of the interlayer in the substantial reservoir. In the 2D model, there is a 2 cm crack in

Figure 1. Schematic diagram of the 2D visualization experiment.
the middle of the interlayer, which simulates a rupturable discontinuous interlayer. The thickness of the bottom water was 8 cm. The permeability and porosity were 2.01 $\mu$m$^2$ and 0.38, respectively.

The experimental procedures mainly included: (1) A sand pack was filled by glass beads of 40-mesh, and formation water was injected into the sand pack to measure the absolute permeability. (2) The glass beads were used to fill the visualization model, and then the model was connected into the experimental system. (3) The formation water (dyed blue) was injected into the visualization model from the bottom to empty air, and then the white oil (dyed red) was injected into the model from the top to empty water in the oil layer at a low flow rate. (4) The formation water was injected into bottom water from the bottom by a constant flow pump. (5) Then the distribution characteristics of fluids were continuously recorded by a high-definition camera, and the production performance of the top horizontal well was measured in time. (6) When the water cut was over 90%, nitrogen was injected from the horizontal well, and then the horizontal well was opened to produce again until the water cut was over 90%. (6) Based on these series of experimental results, the macro- and microanalyses were completed to recognize the migration of the gas phase and the location of the remaining oil. Finally, the mechanisms of antwater invasion were summarized during nitrogen injection and secondary production.

3. RESULTS AND DISCUSSIONS

3.1. Dynamic Production Performance. Figure 3 presents the curves of instantaneous oil production and water cut before and after nitrogen injection. The results of production performance are listed in Table 1. According to the experimental results, there was a period of water-free oil production of about 8 min. During this process, the maximum instantaneous oil production was 0.29 mL/min, and the oil recovery factor was 6.48%. With the rapid growth in water cut, the oil production rate sharply decreased from 0.29 mL/min to about 0.07 mL/min. Then the water cut increased linearly, and the oil production rate gradually decreased. When the water cut exceeded 90%, it was at about 72 min, and the oil production rate was lower than 0.01 mL/min. The corresponding oil recovery factor was only 25.51%. Then, the nitrogen of 0.2 PV was injected into the model from a horizontal well at a flow rate of 10 mL/min under standard conditions. The water cut quickly dropped from above 90% to below 80%, and the oil production rate rose significantly. During the secondary production, the water cut was maintained at 86%–90%, and the maximum oil production was over 0.05 mL/min. By the end of the experiment, the water cut was more than 92%, and the final oil recovery factor was 31.42%.

3.2. Macrosweep Characteristics. 3.2.1. Processes of Water Invasion. Figure 4 illustrates the visualization images of water invasion during production processes. As shown in Figure 4(a)–(c), bottom water breaks through the interlayer crack and advances to the horizontal well at the top of the reservoir, forming a radial flooding profile. The seepage area is smaller, and the flow velocity is higher at the crack of the interlayer. However, the seepage area gradually becomes larger and larger, and the flow velocity becomes lower and lower far away from the bottom water (Figure 4(d) and (e)), which tends to form a dispersed state of the water phase.39–41 As shown in Figure 4(f), when the water cut of the horizontal well exceeds 90%, the corresponding oil recovery factor is only 25.51%. A lot of remaining oil is still stranded on both sides at the crack of the interlayer. It is not easy to produce them without taking any measure of antwater invasion.

It is clear that the remaining oil is formed for the following reasons: (1) For bottom-water reservoirs with fractured interlayers, if cracks are formed due to the pressure difference between the bottom-water and oil layer, bottom water will flow into the reservoir rapidly from fissures. Because the seepage area is narrower near the crack, the flow rate is more prominent near the break. However, the seepage rate gradually decreases when bottom water flows upward from the gap to the horizontal well. The shape of the swept zone presents a circular sector; therefore, a large amount of remaining oil occupies the two sides of the crack near the interlayer. (2) For a homogeneous oil layer, the primary zone of water invasion locates the heel and the middle part of a horizontal well. Otherwise, the infested bottom water migrates upward in a higher permeability zone due to the inlayer heterogeneity along the horizontal well. After most of the horizontal segment is invaded by bottom water, there is still a lot of remaining oil in the unswept zone.

3.2.2. Processes of Nitrogen Injection. Figure 5 shows the macrosweep characteristics of the gas phase during nitrogen injection. Nitrogen preferentially enters the water-channeling
path due to lower seepage resistance, as shown in Figure 5. Due to a broader seepage area at the upper part, the flow velocity of nitrogen is slower, which is conducive to the invaded water being displaced by nitrogen under the effect of gravity differentiation (Figure 5(a)). When nitrogen approaches the crack of the bottom interlayer, the seepage area gradually decreases, resulting in the flow velocity of nitrogen increasing. This phenomenon is helpful for water and gas to migrate from the water-channeling path to both sides of the unswept zones occupied by the remaining oil. Even a part of nitrogen flows into the bottom-water layer from the crack, so the flow velocity further increases, resulting in the dispersion of the gas phase in bottom water. The effect of nitrogen dispersion plays a role in antiwater invasion (Figure 5(b)).

3.2.3. Processes of Secondary Production. Figure 6 presents the distribution state of oil, water, and gas in the secondary production processes after nitrogen is injected. As shown in Figure 6(a) and (b), a large amount of nitrogen exists in the form of a continuous phase in the water-swept range of the upper oil layer; however, part of nitrogen mostly shows a dispersed state in the water-swept range of the middle and bottom oil layers. Under the Jamin effect of dispersed gas, bottom water hardly flows along the original water-channeling path due to a more considerable seepage resistance to enlarge the base-swept zone and mobilize the remaining oil, as shown in Figure 6(c). As shown in Figure 6(d), when water cut is over 90%, a large amount of bottom water still advances to the horizontal well along the original water-channeling path. Still, the nitrogen of the dispersed phase is distributed within the swept zone to make the bottom water turn to both sides of the remaining oil near the crack. Finally, the swept area is expanded to enhance the oil recovery of the bottom-water reservoir. Therefore, the dispersed nitrogen is still in the water-channeling path of the oil layer, which can effectively inhibit

| time (min) | cumulative liquid production (mL) | cumulative water production (mL) | cumulative oil production (mL) | water cut (%) | oil recovery factor (%) | note |
|------------|-----------------------------------|---------------------------------|-------------------------------|---------------|------------------------|------|
| 8 min, 8 s | 1.93                              | 0.00                            | 1.93                          | 0.00          | 6.48                   | Water-free oil production period |
| 50 min, 51 s | 10.12                             | 5.05                            | 5.08                          | 75.56         | 22.49                  | Water cut exceeds 75% during water invasion |
| 72 min, 13 s | 14.62                             | 8.81                            | 5.81                          | 90.59         | 25.51                  | Water cut exceeds 90% during water invasion |
| 104 min, 16 s | 20.88                             | 14.22                           | 6.66                          | 90.66         | 29.65                  | Water cut exceeds 90% again after nitrogen injection |
| 124 min, 36 s | 24.82                             | 17.80                           | 7.02                          | 92.31         | 31.42                  | The end of experiments |

Figure 4. Macroanalysis of water invasion from bottom water to a horizontal well. (Note: The red zone is occupied by oil. The blue zone is occupied by water. The shape of the swept zone is like a circle sector.)
bottom water from upward migrating and significantly decrease the occupied range by the remaining oil. Nitrogen injection plays the role of antiwater invasion and enhancing oil recovery. However, the dispersed nitrogen is prone to coalescence and forming a giant slug of the gas phase. Therefore, the blocking ability gradually becomes poor. A foaming agent can be employed to generate firmer blocking ability foams to strengthen further the effect of antiwater invasion during nitrogen injection in bottom-water reservoirs. During secondary production, nitrogen flows back to the zones near the well to make nitrogen and water form a seepage zone of gas–water in two phases, which increases the seepage resistance of the water phase and relatively enhances the mobility of crude oil.

3.3. Micro Characteristics of Distribution and Migration. Figure 7 shows the distribution characteristics of the dispersed gas in the pores of the oil layer or bottom-water layer. As shown in Figure 7(a), during the nitrogen injection process, a dispersed state formed by the gas phase transforms the oil–water two-phase seepage in the swept zone into an oil–gas–water three-phase seepage, and the seepage resistance of the water phase increases. At the same time, the giant gas slugs in a more extensive distribution range break into many
small gas slugs due to the continuous snap-off effect from one pore throat to another during nitrogen migration. Some small gas slugs are stationary under the Jamin effect to block the water-channeling paths. Then some scattered small gas slugs aggregate and merge to form giant gas slugs again in the reservoir. Therefore, the injected nitrogen relies on a series of dynamic processes, such as breakup, migration, coalescence, and regeneration, to achieve a pleasing effect of antiwater invasion, as shown in Figure 7(a) and (b).

As shown in Figure 8, according to the photos of the dispersed gas phase, the following analysis can be completed. Forming many dispersed slugs in the gas phase is accessible in the nitrogen injection process. Although the gas slugs occupy several pores, resulting in poorer stability, they can still play a role in increasing the seepage resistance of the water phase and resisting the bottom water from invading again. The mobility of dispersed nitrogen is vastly reduced under the Jamin effect at the pore throats in the swept zone or the layer of bottom water, which can effectively decrease the relative permeability of the water phase and even make it immobile irreducible water. In these pore throats, the liquid film of the dispersed gas phase has a slight shape change but is static in the porous medium. The larger-scale dispersed gas phase will rupture into several small slugs during the migration of the liquid films. These broken small gas slugs will merge with other scattered gas slugs to form a new giant gas slug again and almost stationarily occupy several or some pores.

3.4. Mechanisms of Enhancing Oil Recovery. Figure 9 presents the distribution photos of gas, water, and oil in the swept zone in the oil layer during nitrogen injection. Several mechanisms of enhancing oil recovery were discussed as follows.

(1) At the beginning of the nitrogen injection, nitrogen mainly enters the water-channeling path where the seepage resistance is lower, as shown in Figure 9(a). The significant difference in seepage velocity leads to a dispersed gas−water state in the swept zone. The dispersed gas-phase slugs not only increase the seepage resistance of the water phase but also drive the invaded water downward under gravity differentiation. Finally, the continuous water-channeling path is cut off to form many dispersed water slugs. The mobility of the water phase gradually decreases, and even a part of the water phase becomes immobile due to the trapping effect of small gas slugs, as shown in Figure 9(b).

(2) As nitrogen is injected more and more, the number of dispersed gas-phase slugs gradually increases. A portion of the
Gas phase gathers at the top of the oil layer to form continuous gas slugs to drive a large amount of invaded water and a small part of mobile oil downward, as shown in Figure 9(d). The gas slugs disperse in the oil phase, which is the continuous phase, and in the water phase, which is usually the dispersion phase, as shown in Figure 9. That can increase the seepage resistance of the water phase but almost does not change the mobility of the oil phase. Even a part of nitrogen moves into the continuous water phase at the bottom of the reservoir and causes some water to return to the underlying aquifer. Then, more giant gas slugs break into smaller slugs due to the snap-off effect during nitrogen migration, and the scattered small slugs are affected by the shear impact of pore walls when they pass through pore throats; therefore, some small slugs are captured in pores under the Jamin effect. Because the slugs occupy many pores in the water-swept zone, which can block and change the flow direction of bottom water, the subsequently injected nitrogen and the invaded water are diverted to the unswept region.

Figure 9. Dispersed gas-phase slugs in the water-channeling path in an oil layer. (Note: The continuous red or orange zones are occupied by the oil phase. The discontinuous green or blue zones are occupied by the water phase. The zones of dispersed darker spherical particles are occupied by gas slugs.)

In the secondary production processes, the swept area will be further expanded in the oil layer to mobilize the remaining oil on both sides of the water-channeling zone. Therefore, a tremendous amount of nitrogen accumulates in the middle and upper part of the oil layer within the water-swept zone, which can decrease the upward flow velocity of water invasion, increase oil production, and enhance oil recovery in bottom-water reservoirs. However, because of the short effective period of the gas slug, gas phase and foaming agents can generate several steady foams in porous media to effectively block the channeling path of bottom water.42–46

4. CONCLUSIONS

This paper conducted a series of visualization experiments to study the mechanisms of antiwater invasion and enhancing oil recovery by nitrogen injection in a horizontal well. Based on the experimental results, several conclusions were drawn:

1. It is a big challenge to effectively develop bottom-water reservoirs with rupturable interlayers. Bottom water radially advances from the crack of the interlayer to the oil layer. The seepage area at the gap is narrower, resulting in a higher seepage velocity. In comparison, the seepage area is more extensive, far away from bottom water, and the seepage velocity becomes lower, quickly leading to an incredible amount of the dispersed water phase.

2. During nitrogen migration in the water-swept zone, the seepage of oil–water phases changes into the seepage of oil–gas–water phases, which can decrease the relative permeability of the water phase. Meanwhile, nitrogen exists as a dispersed gas slug in the swept zone to increase the flow resistance of the water phase and even make invaded water immobile under the Jamin effect.

3. During nitrogen injection, invaded water is displaced by nitrogen under the effect of gravity differentiation. The injected nitrogen relies on a series of dynamic processes, such as breakup, migration, coalescence, and regener-
ation, to achieve a pleasing effect of antiwater invasion. The gas slugs occupy many pores in the water-swept zone to block and change the flow direction of bottom water, and finally, the swept area can be vastly increased.

(4) In the oil layer, gas slugs disperse in the continuous oil phase and discontinuous water phase to increase the seepage resistance of the water phase but almost do not change the mobility of the oil phase. The swept area is expanded during secondary production to mobilize the remaining oil. A significant amount of dispersed nitrogen decreases water invasion’s upward flow velocity and enhances oil recovery in bottom-water reservoirs. However, because of a short effective period of the gas slug, foaming agents can be used to generate steady foams in antiwater invasion.

AUTHOR INFORMATION

Corresponding Author
Zhaxi Pang — State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, China; orcid.org/0000-0002-1438-360X; Email: pxiad9827@163.com

Authors
Jiajie Chen — State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, China
Dong Liu — Tianjin Branch of China National Offshore Oil Company (CNOOC) Ltd., Tianjin 300452, China
Yuhao Zhou — Department of Physics, University of Fribourg, Fribourg 1700, Switzerland

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c03178

Notes
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