Engineering Advances, 2024, 4(1), 60-70
https://www.hillpublisher.com/journals/ea/
ISSN Online: 2768-7961

Study on Visualization Water Drive Experiment and Mechanism in Bottom Water Reservoir Affected by Seepage Barrier

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How to cite this paper: Dongmei Huang, Chengchao Yu, Jun Ni, Yinglin Luo, Qiaoliang Zhang, Yingzhong Yuan, Ziqi Tang. (2024) Study on Visualization Water Drive Experiment and Mechanism in Bottom Water Reservoir Affected by Seepage Barrier. *Engineering Advances*, 4(1), 60-70.
DOI: 10.26855/ea.2024.02.009

Received: February 15, 2024
Accepted: March 12, 2024
Published: April 9, 2024

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Abstract

Considering the geometric configuration of the bottom water reservoir and the contact mode between the bottom water and reservoir, a visualization water drive experiment method for simulating the influence of the seepage barrier in the bottom water reservoir is established. For bottom water drive reservoirs with different positions and properties of seepage barrier, oil and water movement paths are visually observed, also the mechanism and law of water displacing oil are studied. The results indicate that the bottom water reservoir affected by seepage barriers has seepage mechanisms including bottom water coning, bypass flow, and oil water contact uplift. Bottom water coning occurs if without encountering the seepage barrier. If there is a seepage barrier, a bypass flow of bottom water happens, forming residual oil around the seepage barrier. When the seepage barrier is located in the middle of the oil layer on the plane and at the bottom of the oil layer in the vertical direction, the water-cut rises slowly and the water drive effect is good. For seepage barriers with partial permeability, the development effect is better. This study lays a theoretical foundation for analyzing residual oil distribution law and drawing up development adjustment treatments in bottom water reservoirs.

Keywords

Bottom water reservoir, Seepage barrier, Visualization experiment, Water drive mechanism, Water cut rise law

1. Introduction

Bottom water reservoir is a very important type of reservoir, which has been found in both sandstone and carbonate reservoirs [1, 2]. Especially on the offshore, bottom water reservoirs are common, some of which have strong natural water body energy [3-5]. This type of oil reservoir commonly has multiple sets of calcareous interlayers in the vertical direction, forming seepage barriers that hinder the flow of oil and bottom water [6, 7]. A large number of studies show that the existence of seepage barriers in bottom water reservoirs can effectively alleviate bottom water coning and prevent the rise of bottom water. However, different types of seepage barriers have different abilities to prevent the rise of bottom water, and their recovery degrees are also different. Therefore, in the development process of the bottom water reservoir, it is of great significance to analyze the impact of different seepage barriers on the rise of bottom water. Some scholars [8-11] used theoretical calculations and numerical simulation methods to study the influence of seepage barriers (interlayers) on water breakthrough time and water drive law of bottom water reservoirs, and they gained important inclusions. However, the understanding of the water drive mechanism in the bottom water reservoir affected by seepage barriers is still not very clear.

Physical simulation experiment is an important means to study the water drive mechanism in the bottom water reservoir [12-14]. The simple approach is to conduct water drive experiments in natural or artificial cores, but it is difficult to reflect the sweep status of bottom water. Two-dimensional (2D) glass plate models [15, 16] are made through two glass cemented or fixed bolts, in which the sands are filled. The models can visually observe the flow of fluid, but they do not fully consider the geometric configuration of the bottom water reservoir (such as the length/thickness ratio of the model), the contact mode between the bottom water and the reservoir, and the influence of seepage barrier on the flow in oil layer. 3D large-scale physical simulation experiments can truly simulate fluid flow under formation conditions, but the model size is large, and the equipment is expensive, also the experimental cycle is time-consuming [17-19]. Therefore, considering the geometric characteristics and oil-water contact relationship of the bottom water reservoir, physical models of the bottom water reservoir with different positions and properties of seepage barriers are made. A visualization water drive experiment method is established to simulate the influence of seepage barriers in the bottom water reservoir. The mechanism and water drive law in the bottom water reservoir are studied, laying a theoretical foundation for studying remaining oil distribution law and drawing up development adjustment treatments in the bottom water reservoir.

2. Improved physical simulation experiment method

The improved 2D visualization model design for the bottom water reservoir is shown in Figure 1. The model consists of three parts: the oil layer, the bottom water layer, and the simulated well. The model is composed of two transparent flat glass plates in front and behind with the same size. A slot is milled at the bottom of the transparent glass plate behind to fill the bottom water. Above the bottom water slot, a rectangular pit is milled using a numerically controlled machine tool to act as an oil layer, where the quartz sand powder is evenly filled and compacted by rolling to ensure uniformity and flatness. There is a comb-shaped groove between the bottom water slot and the oil layer as the seepage channel, and a fine sieve is installed above the seepage channel and the bottom of the oil layer to prevent sand particles from invading the bottom water slot or entering into the seepage channel, causing an impact on the flow of bottom water. The front glass plate has a convex platform that matches the sand-filling pit of the glass plate behind, which is conducive to compacting the sand. The transparent plate behind is covered by the transparent plate in front. Two transparent glass plates and the surrounding area of the model are bonded and sealed with epoxy resin. There are drainage ports at the left and right ends of the slots of the transparent plate behind, which can discharge water or oil from the bottom water slot.

The method of making a vertical or horizontal well in the model is as follows. Firstly, drill a small vertical hole or mill a horizontal groove at the corresponding position in the model, then fill it with a cylindrical sieve as the vertical or horizontal well, finally connect a hose to the end of the sieve to lead it out. The model is designed with an inlet and outlet that can be connected to external pipelines and it is ensured to be sealed.

The seepage barrier is set up in the model according to the needs. The setup method is as follows. Firstly, make one or several convex elongated "pins" on the transparent glass plate behind the seepage barrier. The transparent glass plate in front has a slot facing the seepage barrier. Then, embed the seepage barrier on the transparent glass plate behind into the slot of the transparent glass plate in front. It can ensure the blocking effect of the seepage barrier, and reduce incomplete blocking caused by gaps between the end face of the seepage barrier and the contact surface of the transparent glass plate in front. Finally, fill the slot with sealant to further ensure the sealing effect.

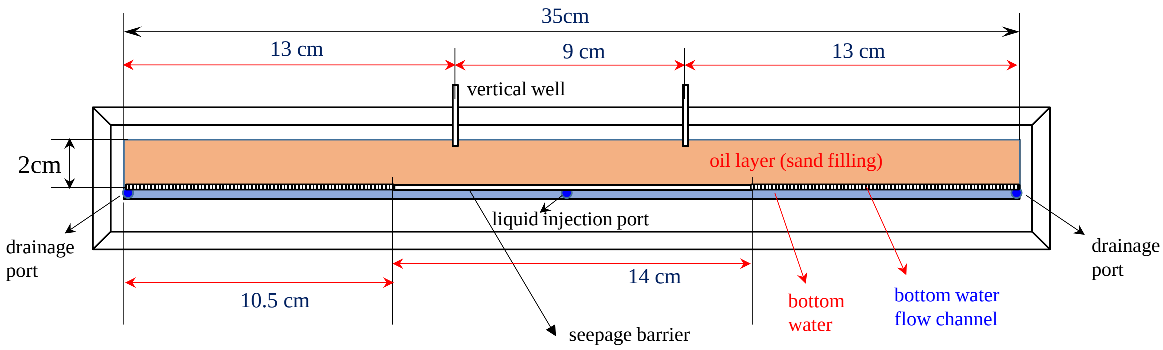


Figure 1. Design diagram of an improved 2D model for the bottom water reservoir.

During the experiment process, dyeing water is injected into the model to achieve the goal of visualization drive and intuitively observe the impact of the seepage barrier on the water drive mechanism. In order to clearly observe the movement path of bottom water without too many interferences and make the model be close to the actual geometric parameters of the reservoir as much as possible, the model length/thickness ratio cannot be too large or too small. The actual physical model is shown in Figure 2, with an effective size of 35cm × 2cm × 0.2cm for the oil layer and a length of 14cm for the seepage barrier. This visible 2D model is close to the actual geometric configuration of the oil reservoir. It is lightweight, more visible, and the experimental cycle is short.

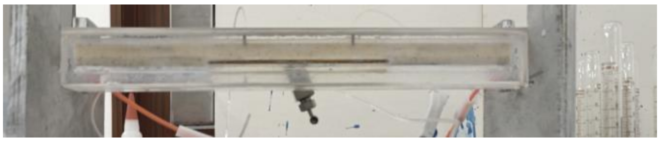


Figure 2. Actual 2D visualization model.

3. Design of physical simulation experiment for water drive in bottom water reservoir affected by seepage barrier

3.1 Experiment instrument and equipment

The main instruments and equipment used in the experiment include:

(1) Pump: dual cylinder pump with constant speed and pressure (operating temperature: room temperature ~160 ℃; range of flow rate: 0~30mL/min; accuracy: 0.01mL/min; bearing pressure: 70MPa), vacuum pump.

(2) High-pressure intermediate vessel (200mL, bearing pressure: 70MPa).

(3) 2D physical simulation model, customized.

(4) High-definition camera and bracket.

(5) High-precision pressure sensor.

(6) Measuring cylinders, valves, high-pressure pipelines, etc.

3.2 Experiment material

Experiment materials include:

(1) Quartz sand: fill quartz sand with different mesh sizes to achieve different porosities and permeabilities.

(2) Experimental oil: white oil (viscosity 10mPa. s).

(3) Formation water: compounded in the laboratory based on the proportion of ion content in actual formation water.

(4) Methylene blue: dye injected water to distinguish oil and water and observe experimental phenomena.

3.3 Experiment procedure

The experiment procedures are as follows:

(1) Process, manufacture, seal, and assemble 2D visualization model.

(2) Connect the pipeline and establish the experiment workflow (Figure 3).

(3) Pump vacuum and saturate the model with water at a rate of 0.1mL/min, then slowly saturate oil until there is no water flowing out at the outlet.

(4) Start the bottom water drive at an injection rate of 0.1mL/min. To avoid discontinuous points like the rise of bottom water, the external water source enters the slot at the bottom of the model through an external pipeline. The oil in the slot is firstly discharged until the slot is fully filled with dyeing bottom water. The contact mode between the bottom water and the oil layer is entire, which can ensure the continuous advancement of bottom water during the drive process. During the experiment, the output liquid is continuously measured; the pressure and oil-water movement status are monitored and recorded in real time until the water drive ends up.

(5) Put experiment equipment in order, process and analyze experiment data.

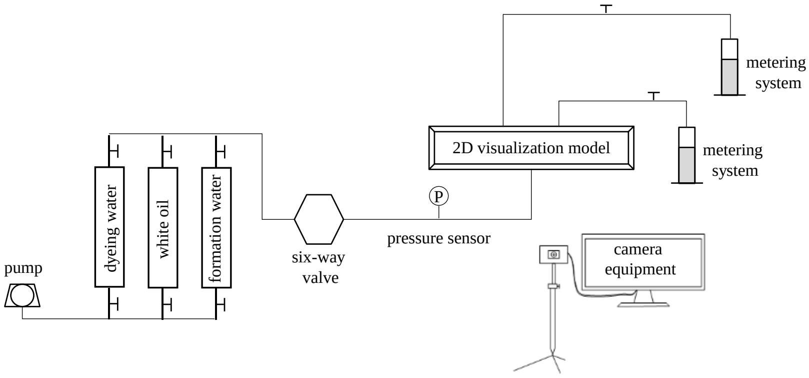


Figure 3. 2D visualization experiment workflow.

3.4 Overall experiment design

The overall design aim of the experiment is to study the water drive mechanism in the bottom water reservoir affected by the seepage barrier, taking into account the changes in the position and physical properties of the seepage barrier. Six sets of 2D physical simulation experiments are designed (Table 1). Among them, the ratio of the length of the seepage barrier to the oil layer is 0.4, and the production wells are all vertical wells.

Table 1. Design of 2D physical simulation experiments

Experiment No.	Design parameters of seepage barrier			
	Permeability of model	Vertical position	Plane position	Permeability of barrier
1	867mD	No barrier	No barrier	No barrier
2	872mD	Bottom of oil layer	Middle of oil layer	Impermeable (0mD)
3	948mD	Middle of oil layer	Middle of oil layer	Impermeable (0mD)
4	882mD	Middle of oil layer	Edge of oil layer	Impermeable (0mD)
5	815mD	Bottom of oil layer	Middle of oil layer	Partially permeable (5mD)
6	839mD	Middle of oil layer	Middle of oil layer	Partially permeable (5mD)

4. Analysis of water drive mechanism in bottom water reservoir affected by seepage barrier

4.1 Characteristic and mechanism of water drive in bottom water reservoir

4.1.1 Without seepage barrier

Due to the flow resistance in the bottom water slot being small, the injected dyeing water enters the bottom water slot first and the oil in the slot is discharged through the drainage port. After the bottom water slot is filled with bottom water, the contact mode between the bottom water and oil layer is entire before the bottom water drive.

If there is no seepage barrier, the production well section of the bottom water reservoir is located at the top of the oil layer, with a certain water avoidance height from the bottom of the well section to the bottom water. After the bottom water drive starts, a "funnel" shaped pressure distribution area will form around an oil well. The formation pressure gradually increases from the bottom of the well along the direction of the radial supply boundary. Due to the fact that the well produces oil from the oil layer, the pressure in the oil layer is lower than the pressure in the bottom water. Because of the influence of the pressure difference (power) between oil and water, water coning appears at the bottom of the vertical well. At the same time, because the density of water is greater than that of oil, the effect of gravity (resistance) suppresses the formation of water coning. As the water drive continues, under the combined effect of drive pressure difference and gravity, the range of water coning gradually expands, and the water coning between two wells are connected together. In the vertical direction, the height of water coning becomes larger and larger, gradually advancing towards the bottom of production well and protruding into it. After breakthrough of water coning, the sweep range of bottom water gradually expands, and residual oil is enriched at the edge of the structure (Figure 4).

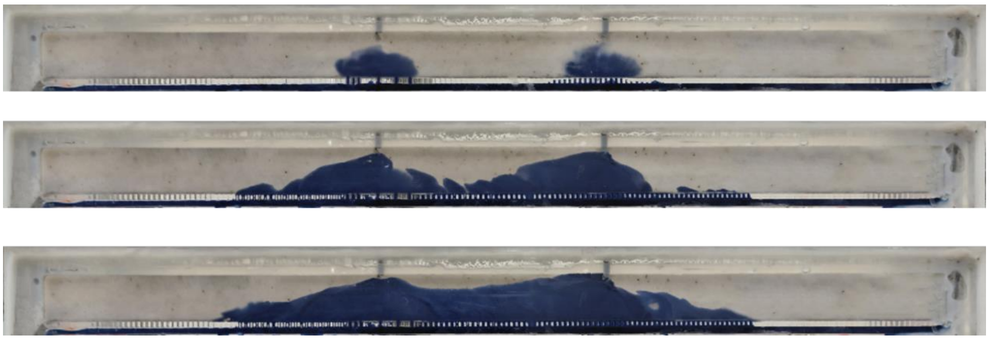


Figure 4. Movement path of oil and water in bottom water reservoir without seepage barrier (Experiment 1).

4.1.2 The impermeable seepage barrier is located at the bottom of oil layer in vertical direction and the middle of oil layer on the plane

The seepage barrier is a rock mass that blocks fluid flow within a reservoir system, which can to some extent prevent bottom water coning. For an impermeable seepage barrier with poor physical properties, it is difficult for bottom water to pass through it vertically under the normal production pressure difference of the reservoir, and can only flow around both sides of the seepage barrier. From the pressure distribution, it can be understood that the seepage barrier is an impermeable boundary with finite length, and there is a weak pressure sweep area below it. Therefore, bottom water flows along the main pressure drop direction preferentially, bypassing the impermeable seepage barrier, which is the bypass flow of bottom water. When the impermeable seepage barrier is located at the bottom of the oil layer in the vertical direction and the middle of the oil layer on the plane, the bottom water flows around the seepage barrier, making it difficult to drive the oil in the area above the seepage barrier between wells, and the remaining oil is also formed at the edge of oil reservoir due to the inability of the bottom water to reach (Figure 5).

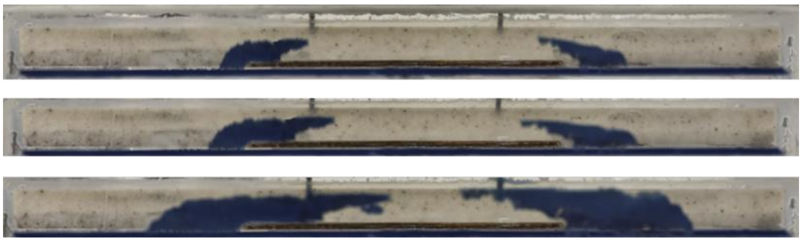


Figure 5. Movement path of oil and water in bottom water reservoir with seepage barrier (Experiment 2).

4.1.3 The impermeable seepage barrier is located in the middle of the oil layer in the vertical and plane direction

When the impermeable seepage barrier is located in the middle of the oil layer in vertical and plane direction, due to the blocking effect of the seepage barrier, the bottom water mainly flows towards the upper part of the seepage barrier, and a small amount of bottom water can sweep the area below the seepage barrier, reducing the sweep coefficient in the bottom water reservoir. Residual oil also forms at the edge of the oil reservoir due to the difficulty of bottom water to reach there (Figure 6).

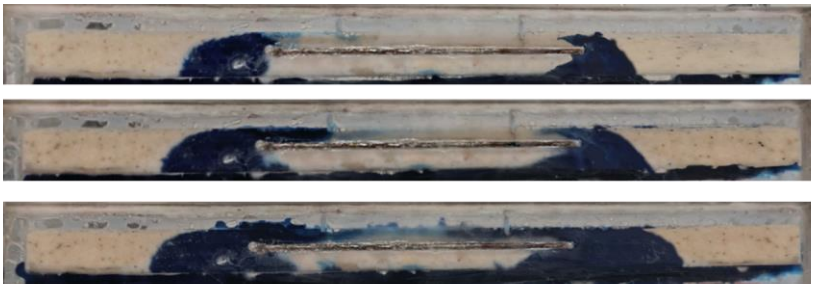


Figure 6. Movement path of oil and water in bottom water reservoir with seepage barrier (Experiment 3).

4.1.4 The impermeable seepage barrier is located in the middle of oil layer in vertical direction and the edge of oil layer on the plane

When the impermeable seepage barrier is located in the middle of the oil layer in the vertical direction and the edge of the oil layer on the plane, the bottom water flows around the edge (right side) of the seepage barrier, and the water cannot drive oil from the left side. For the left vertical well, only the water drive in a single direction is effective, thus the oil layers underlying and overlying the seepage barrier are prone to forming residual oil (Figure 7).

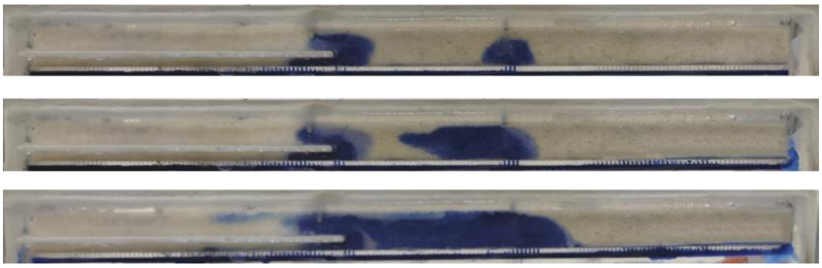


Figure 7. Movement path of oil and water in bottom water reservoir with seepage barrier (Experiment 4).

4.1.5 The partially permeable seepage barrier is located at the bottom of oil layer in vertical direction and the middle of oil layer on the plane

When the partially permeable seepage barrier is located at the bottom of the oil layer in the vertical direction and the middle of the oil layer on the plane, the bottom water flows around the seepage barrier from the left and right sides. Due to the partial permeability of seepage barrier, some bottom water can flow through it. Residual oil is easily formed between production wells in the oil layer above the seepage barrier, and the edge of the reservoir also forms residual oil due to the inability of bottom water to reach (Figure 8).

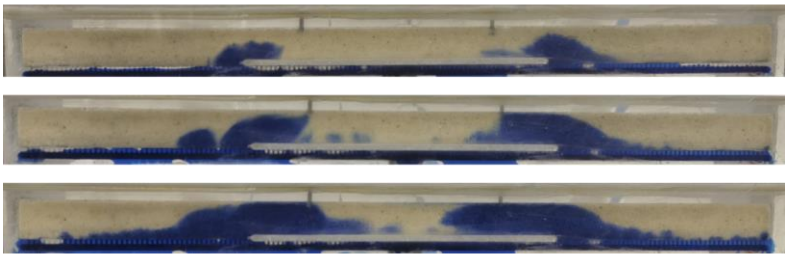


Figure 8. Movement path of oil and water in bottom water reservoir with seepage barrier (Experiment 5).

4.1.6 The partially permeable seepage barrier is located in the middle of oil layer in vertical and plane direction

When the partially permeable seepage barrier is located in the middle of the oil layer in a vertical and plane direction, the bottom water flows around the seepage barrier from the left and right sides. Due to the partial permeability of the seepage barrier, some bottom water can flow through it. The bottom water is easy to sweep the oil layer below the seepage barrier, while the area above seepage barrier and the edge of reservoir are difficult to be swept, leading to generation of residual oil (Figure 9).

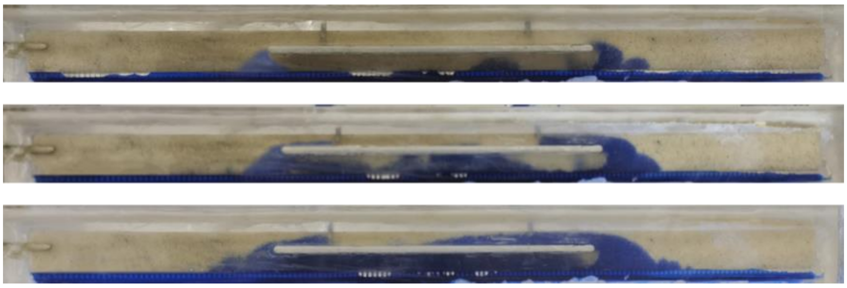


Figure 9. Movement path of oil and water in bottom water reservoir with seepage barrier (Experiment 6).

4.1.7 Water drive mechanism under complex conditions

Due to "abnormal" reasons such as model leakage, model repair, and water channeling at the edges of the model, the phenomena including edge water propulsion, edge water pollution, and bottom water coning are observed (Figure 10).

Due to the incomplete discharge of gas in the bottom water slot, it acts as a seepage barrier, which hinders the displacement of oil by bottom water and forms residual oil. At the same time, the phenomenon of bottom water coning occurred again in the later stage of vertical well re-opening (Figure 11).

Under different well types and abnormal production conditions, the phenomenon of bottom water coning and horizontal well cresting are clearly observed during the water drive experiment in the bottom water reservoir. Due to sand production in the oil layer, the production well appears sand plug, which prevents the normal production of wells and significantly reduces the sweep coefficient of the bottom water drive (Figure 12).

During the experiment, it is also observed that when there is a small blocky seepage barrier in the reservoir, the bottom water can almost surround it. If there is a large blocky seepage barrier, bottom water can only surround part of the barrier block after bypass flow (Figure 13).

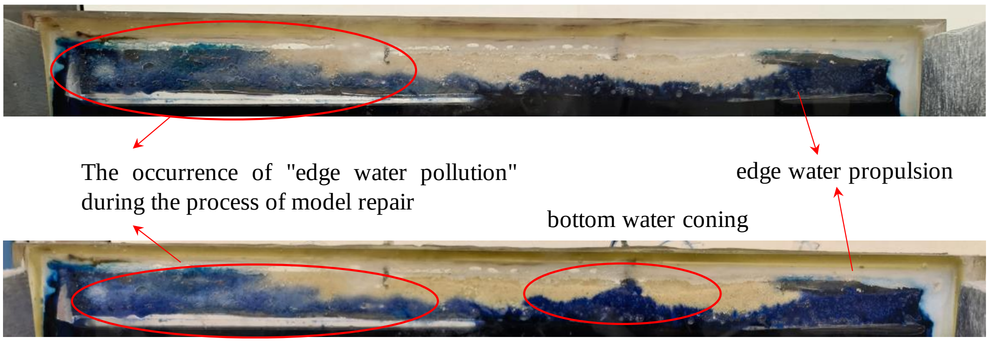


Figure 10. Coning phenomenon due to the influence of multiple factors.

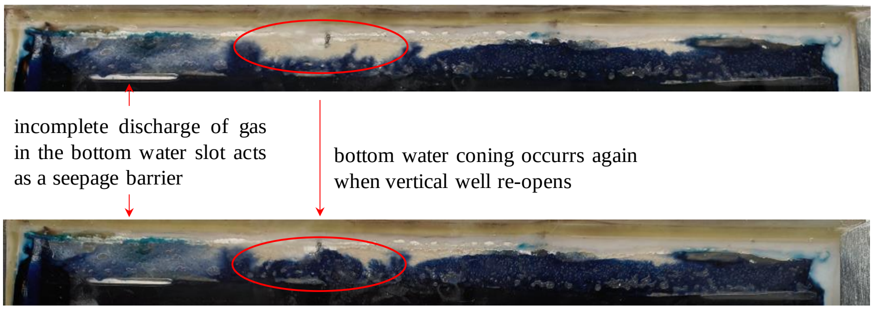


Figure 11. The impact of seepage barrier on bottom water drive.

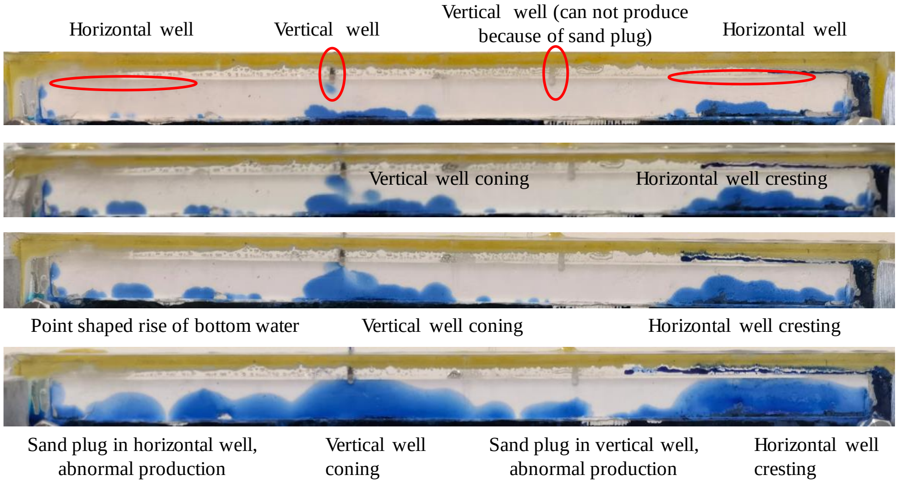


Figure 12. Water drive characteristics in bottom water reservoir at different production conditions.

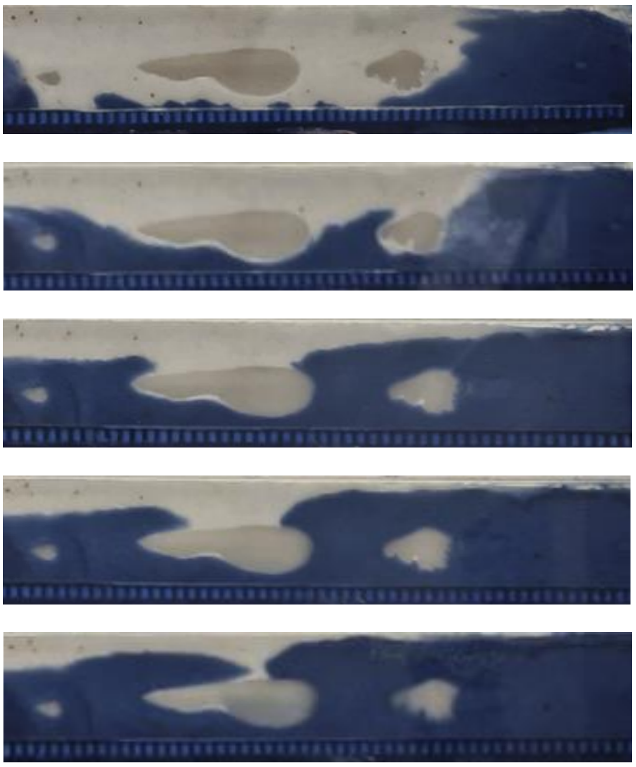


Figure 13. Bypass flow phenomenon of bottom water when encountering blocky seepage barrier.

Overall, the basic characteristics of bottom water flow when encountering a seepage barrier are as follows. If the seepage barrier is in the middle of oil layer in vertical direction, the bottom water mainly flows towards upper area of the seepage barrier, and a small amount of bottom water sweeps the area below the seepage barrier. When the seepage barrier is located at the edge of oil layer on the plane, bottom water flows around the other end of seepage barrier to displace oil, and only the water drive in a single direction is effective. When the seepage barrier is at the bottom of oil layer in vertical direction, bottom water flows towards upper partial area of the seepage barrier, making it difficult to displace the oil above the seepage barrier between wells. On the other hand, the rise of the oil-water contact occurs synchronously with the expansion of the bottom water (water cone) sweep range. Under the control of the hydrodynamic field of the bottom water reservoir, when the bottom water rises irregularly at the initial point, the oil-water contact will gradually connect together and show a phenomenon of overall uplift. When bottom water encounters the seepage barrier, the oil-water contact undergoes deformation, making it difficult to connect into one piece.

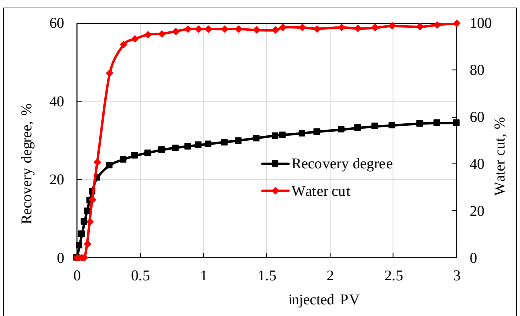
4.2 Comparative analysis of water drive effect in bottom water reservoir

The results of water drive experiments 1-6 are shown in Table 2 and Figure 14. In Experiment 1, there is no seepage barrier, with a water breakthrough time of 0.088PV and a recovery degree of 34.4%. In experiments 2-4, when there is impermeable seepage barriers, due to the bypass flow of bottom water, it is easier to reach the production well near the seepage barrier, resulting in earlier water breakthrough time. Due to the difficulty of bottom water reaching the overlying and underlying oil layer of the seepage barrier, the recovery degree of experiment 2 and experiment 3 decreased, while experiment 2 to some extent suppressed the bottom water coning, resulting in an increase in recovery degree. In experiments 5-6, because the seepage barrier has a certain permeability, some of the bottom water can flow through the seepage barrier, while the amount of bottom water flowing towards the production well near the seepage barrier decreases. Compared with experiments 2-3, water breakthrough times in experiments 5-6 lag behind. Due to the influence of a seepage barrier with partial permeability, bottom water can partially displace the oil blocked by the seepage barrier, resulting in higher recovery degree and better oil displacement effect.

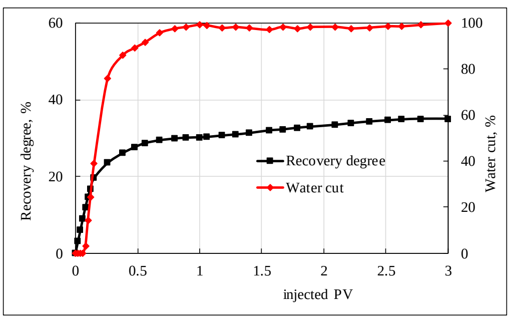
Table 2. Results of bottom water drive experiments

Experiment No.	Water breakthrough time, PV	Recovery degree, %
1	0.088	34.40
2	0.082	35.01
3	0.084	33.49
4	0.073	27.95
5	0.094	39.88
6	0.085	37.16

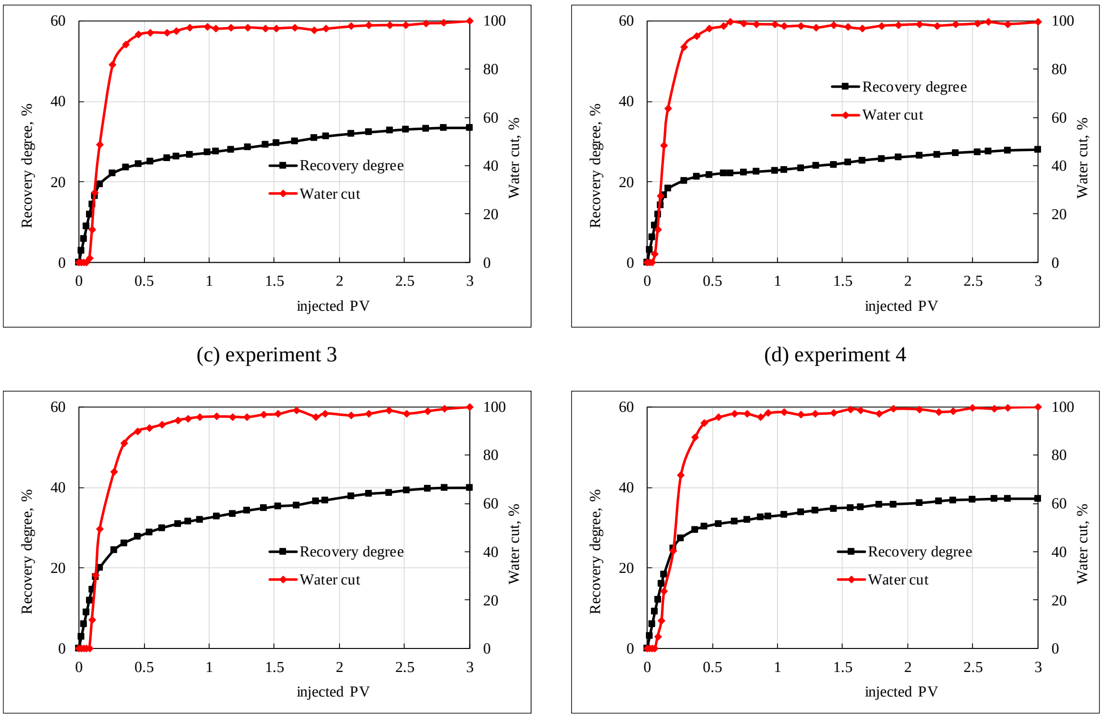
Comparing the results of water drive experiments with different positions of seepage barriers, when the seepage barrier is located at the edge of the oil layer on the plane, the area blocked by the seepage barrier cannot be effectively displaced. Only the water drive at the other edge or direction is effective, thus the drive effect is poor, with a recovery degree of 27.95% in Experiment 4. When the seepage barrier is located at the bottom of the oil layer in the vertical direction, only the overlying layer of the seepage barrier is difficult to be swept, with a high recovery degree of 35.01% in Experiment 2. If the seepage barrier is located in the middle of the oil layer in the vertical direction, both the overlying and underlying layer of the seepage barrier are difficult to be swept, with the recovery degree decreased to be 33.49% in Experiment 3.



(a) experiment 1



(b) experiment 2



(c) experiment 3 (d) experiment 4

(e) experiment 5 (f) experiment 6

Figure 14. Relationship between water cut and recovery degree with injected PV in different experiments.

4.3 Analysis of water cut rise law of water drive in bottom water reservoir

The relationships between water cut and recovery degree in bottom water drive experiments with different positions and properties of seepage barriers are shown in Figure 15 and Figure 16. It can be seen that when the seepage barrier is located at the edge of the oil layer on the plane, the water cut rises faster. In the vertical direction, when the seepage barrier is located in the middle of the oil layer, water breakthrough time is faster, and the rise of water cut shows the characteristics of slow first and then fast. When the seepage barrier is located in the middle of the oil layer on the plane and at the bottom of the oil layer in the vertical direction, the water cut rises slowly. When the seepage barrier has partial permeability, water breakthrough time is slower, and the velocity of water cut rise is slightly slower than the case when the seepage barrier is impermeable.

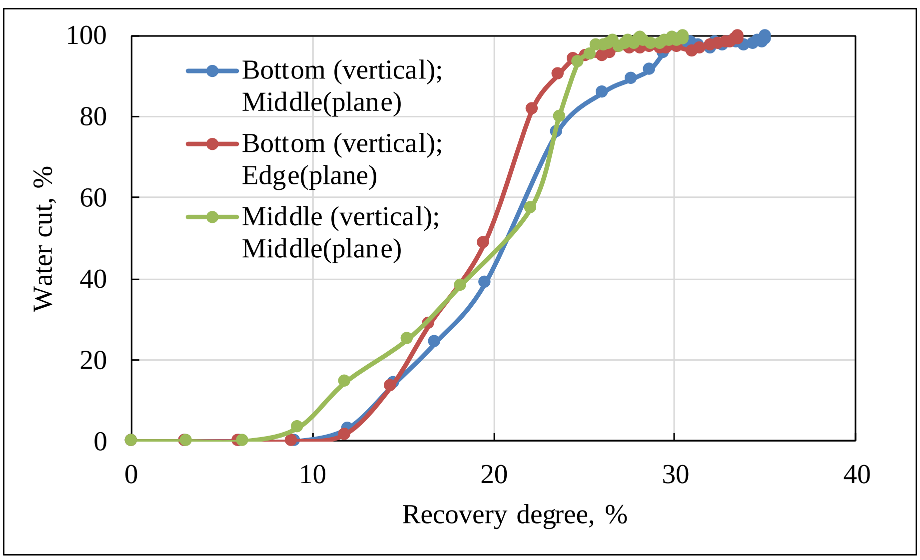


Figure 15. The relationships between water cut and recovery degree in bottom water drive experiments with different positions of seepage barriers.

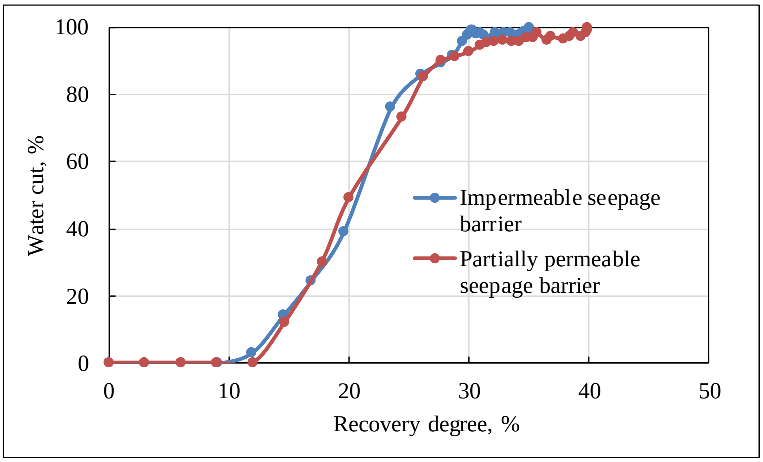


Figure 16. The relationships between water cut and recovery degree in bottom water drive experiments with different properties of seepage barriers.

5. Conclusions

(1) The visualization water drive experiment method for simulating the impact of seepage barriers in the bottom water reservoir is improved. Through transparent glass plates and internal seepage barriers in the model, it is convenient and intuitive to observe bottom water movement characteristics and explore water drive laws. The overall structure of the 2D visualization model is simple, with low manufacturing difficulty and cost. The experiment is easy to operate and the experimental cycle is short.

(2) Bottom water reservoir affected by the seepage barrier has seepage mechanisms including bottom water coning, bypass flow, and oil water contact uplift. Bottom water coning occurs if without encountering the seepage barrier. If there is a seepage barrier, a bypass flow of bottom water happens, forming residual oil around the seepage barrier. The rise of the oil-water contact occurs synchronously with the expansion of the bottom water (water cone) sweep range.

(3) Due to the presence of a seepage barrier, the water sweep coefficient and recovery degree in the bottom water reservoir decreases in general. When the seepage barrier is located at the edge of the oil layer on the plane and in the middle of the oil layer in the vertical direction, water cut rises rapidly and the water drive effect is poor. If the seepage barrier is located in the middle of the oil layer on the plane and at the bottom of the oil layer in the vertical direction, the water cut rises slowly and the water drive effect is better. For the seepage barrier with partial permeability, the displacement effect is better.

Funding

The authors thank the National Natural Science Foundation of China (U22B2074) for supporting this work.

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