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Research Article

Experimental Study on Production Characteristics of Bottom Water Fractured-Vuggy Reservoir

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To assess the high-pressure production characteristics of double-vug reservoirs with bottom water in the Tahe Oilfield, in this study, a high-pressure physical simulation experiment apparatus is built for double-vug reservoirs with bottom water. The high-pressure production characteristics of "vug-fracture-vug" reservoirs under different bottom water characteristics are studied experimentally, and fracture-vug relationship and oil recovery rates are explored. According to the findings, the oil recovery rate significantly affects the development effect of double-vug reservoirs with bottom water, and bottom water provides sufficient energy for reservoir development. Furthermore, considering the possible occurrence of water invasions, the production rate control must receive close attention in the development process to avoid strong water channeling. Constant-pressure bottom water has sufficient energy and can quickly replenish vug energy. Therefore, the recovery percentage and bottom water invasion and retention volume of fractured-vuggy reservoirs with constant-pressure bottom water are higher than those of fractured-vuggy reservoirs with constant-volume bottom water. Under the appropriate control of production factors, the presence of bottom water can noticeably improve the development effect of fractured-vuggy reservoirs.

1. Introduction

Carbonate reservoirs in the Tahe Oilfield are typical fractured-vuggy reservoirs, which generally contain edge and bottom water. In the development process of such reservoirs, premature water breakthrough often causes an excessively fast increasing water content and a precipitously declining production [1, 2]. Moreover, in the Tahe Oilfield, vuggy carbonate reservoirs with bottom water are buried in deep strata with a formation pressure of about 50 MPa and a formation temperature above 120°C [3, 4]. To study the high-pressure physical properties of vuggy reservoirs with bottom water, laboratory high-pressure experimental models must be built, as ordinary experimental models (such as ordinary glass etching models) cannot endure high-temperature or high-pressure environments [5–7].

So far, few experiments have conducted physical simulations of fractured-vuggy reservoirs. Existing studies on fractured-vuggy reservoirs (both in China and internationally) mostly focused on their production performance characteristics. Ozkan et al. [8] explored the single-well production characteristics of naturally fractured reservoirs under constant-pressure boundary conditions. Olarewaju et al. [9] built a mathematical model suitable for naturally fractured or vugular reservoirs with a radial discontinuity around the wellbore, with which they analyzed the production performance of reservoirs. Guo et al. [10] conducted a case study on the Campeche Bay, Mexico, and modeled it theoretically. Goudarzi et al. [11] built physical models for fracture networks using sandstone cores, and studied the laws of fluid exchange between matrix blocks and fractures as well as the parameters influencing the mechanism of fracture permeability. Li et al. [12] prepared a large-sized porous physical model suitable for the heterogeneity of carbonates and examined oil displacement by water in cores using visualization technology.

Chinese scholars attach great importance to the physical simulation of fractured-vuggy reservoirs through experiments and have developed physical models for both fractured-vuggy and vuggy carbonate reservoirs. Zheng et al. [13, 14] performed physical experiments using carbonate cores, concluding that the recovery efficiency of fractured-vuggy reservoirs with bottom water is related to the bottom water volume.

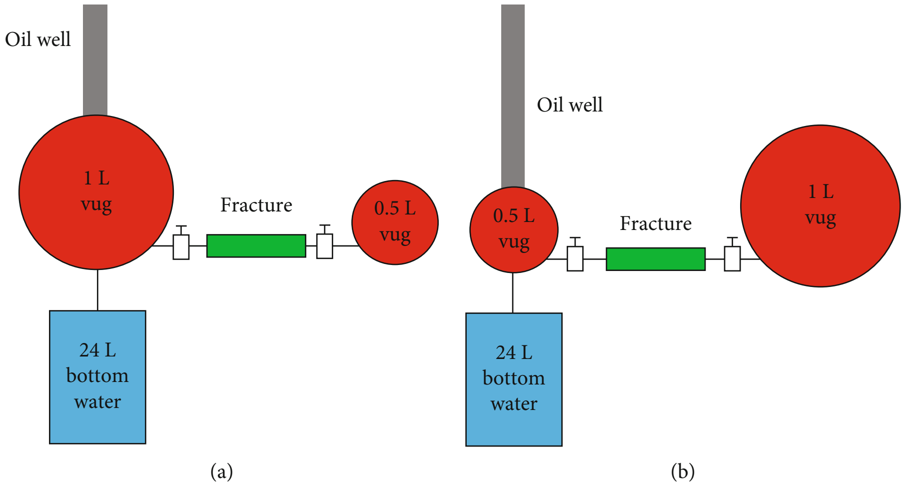


Figure 1: Schematic diagram of the high-pressure physical simulation experiment model for (a) bottom water connected to the large vug and (b) bottom water connected to the small vug.

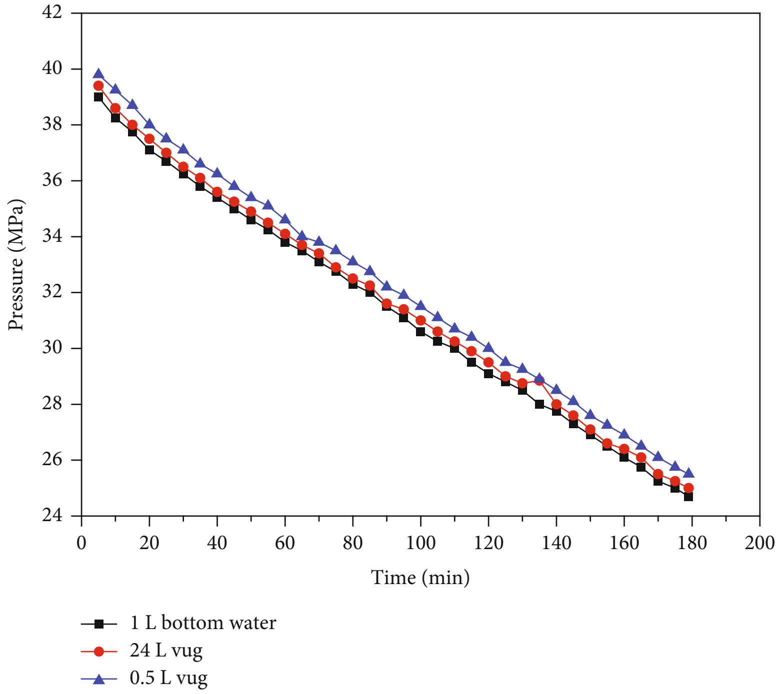
(a)

(b)

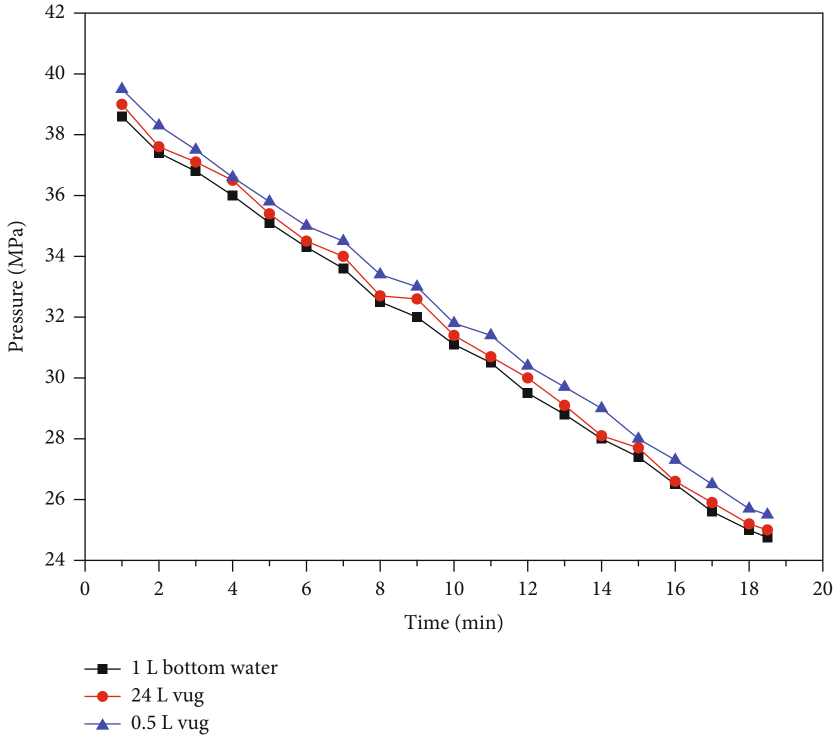
Figure 2: Pictures of high-pressure physical simulation experiment model for (a) bottom water connected to the large vug and (b) bottom water connected to the small vug.

Liu et al. [15] carried out two-dimensional physical simulation experiments on the production performance of vuggy reservoirs with bottom water and found it to be closely related to the connection type and energy of bottom water. Wang et al. [16] performed visual physical simulation experiments on fractured-vuggy reservoirs and found that injecting water into the bottom of a reservoir effectively improves the development effect of the reservoir; moreover, the intensity of water injection affects both water breakthrough time and recovery percentage. Rong et al. [17] studied fractured-vuggy reservoirs with different interwell connection types using tracers, characterizing fracture-vug connection structures, and improving the water drive effect of fractured-vuggy reservoirs. Zhao et al. [18] probed into the fluid production characteristics and laws of fractured-vuggy reservoirs. Qian et al. [19] explored how the salinity and ion content of injected water affect the recovery efficiency of reservoirs based on carbonate core displacement tests. They reached the conclusion that low-salinity water drive modifies the surface wettability of carbonates, thus increasing recovery efficiency.

Generally, physical simulation experiments are performed on fractured-vuggy reservoirs using physical



(a)



(b)

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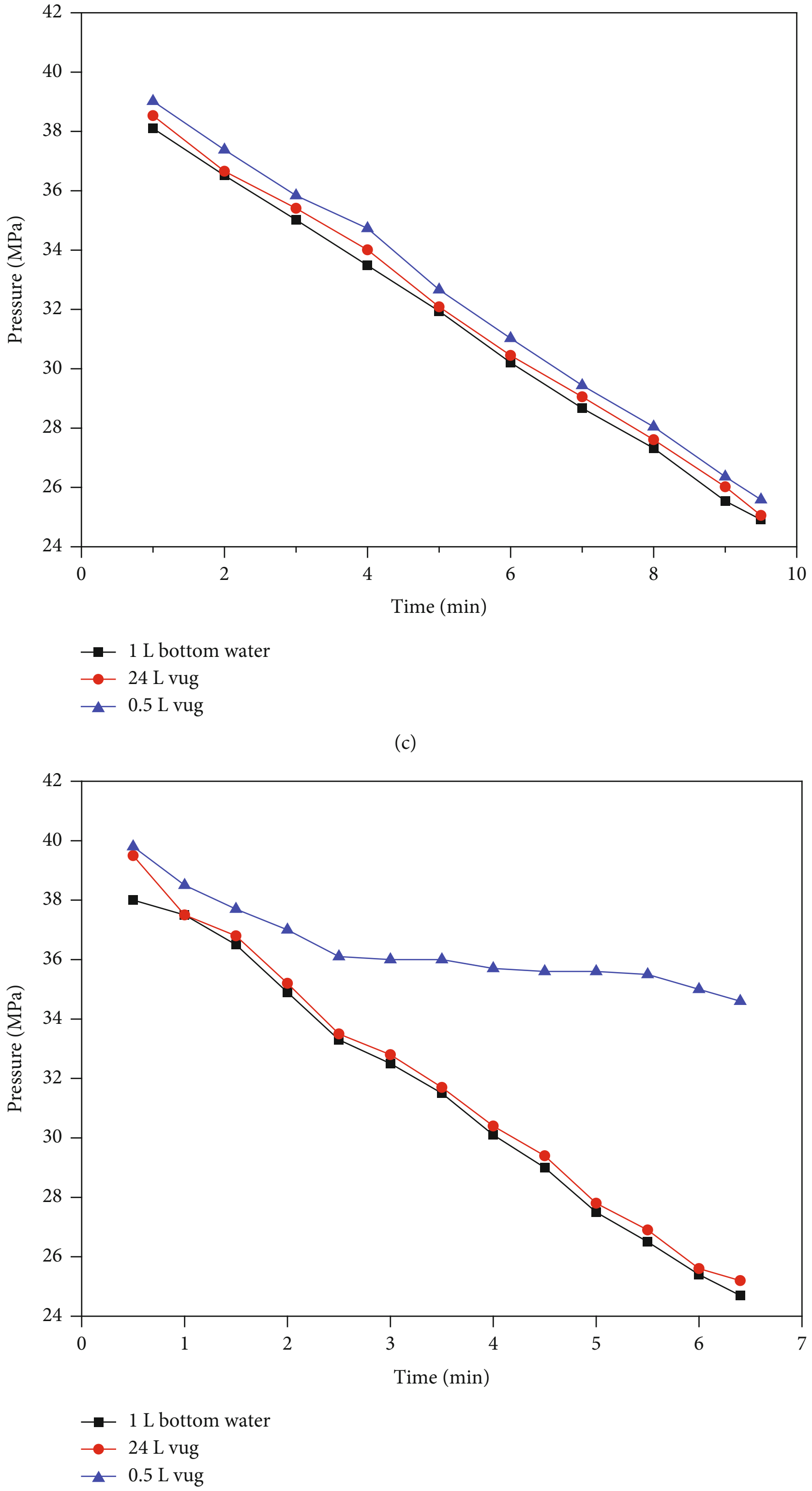


(c)

(d)

Figure 3: Pressure variation curves in high-pressure physical property experiments under connection type I (different production rates with (a) 1 mL/min, (b) 10 mL/min, (c) 20 mL/min, and (d) 30 mL/min).

modeling methods such as all-straight well core samples, simulation of fracture generation with unconsolidated sand pack, fracture generation with cores, and vug modeling [20–23]. With regard to carbonate reservoirs with developed vugs, mainly full-diameter cores are used for physical simulation [24–26]. In apparatus modeling, similarities in

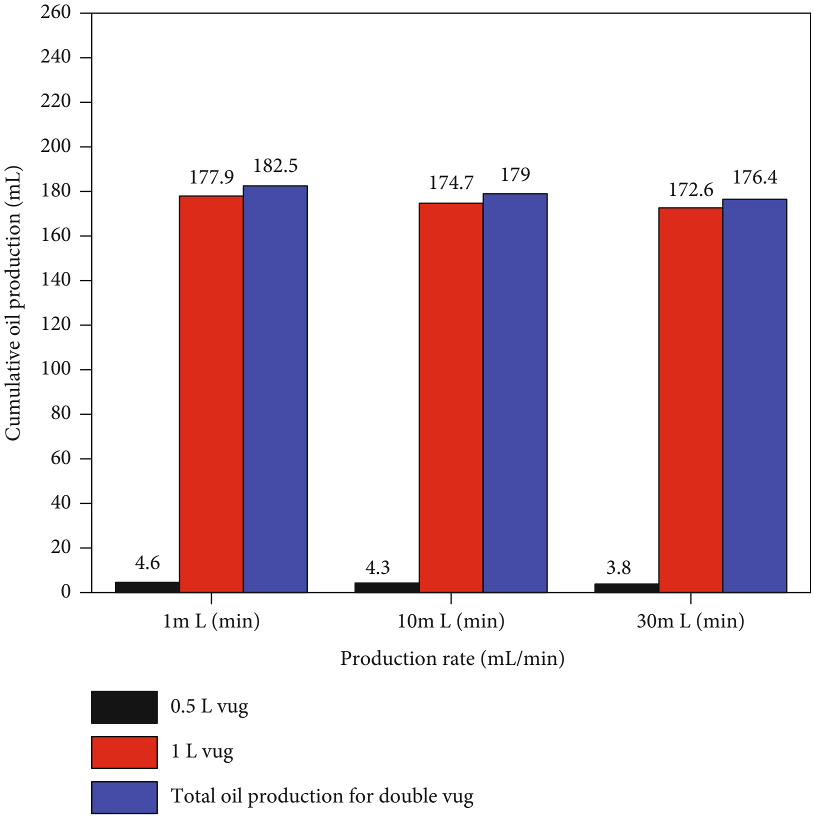


Figure 4: Column chart of cumulative oil production in high-pressure physical property experiments under connection type I (different production rates).

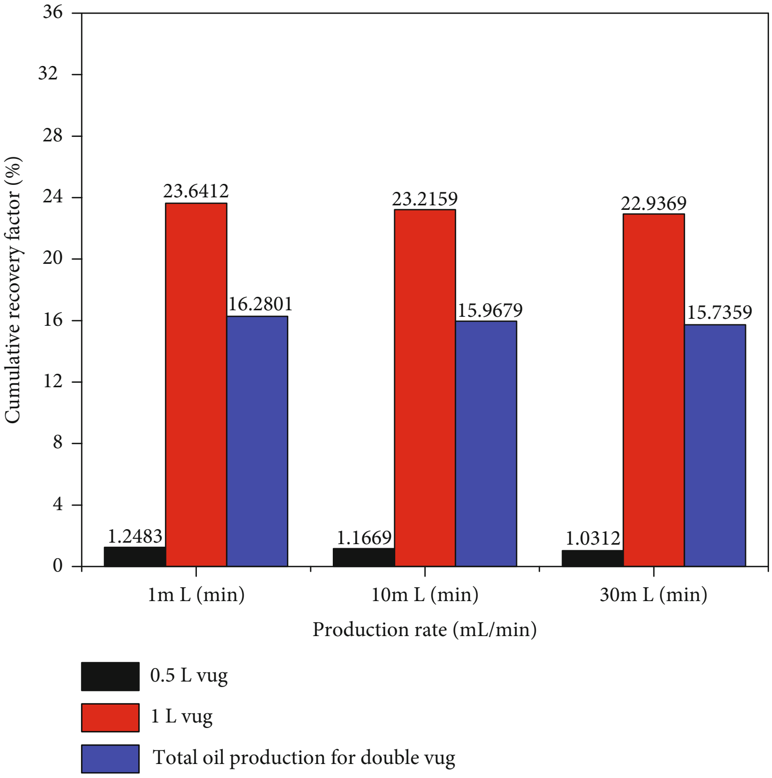


Figure 5: Column chart of cumulative recovery factor in high-pressure physical property experiments under connection type I (different production rates).

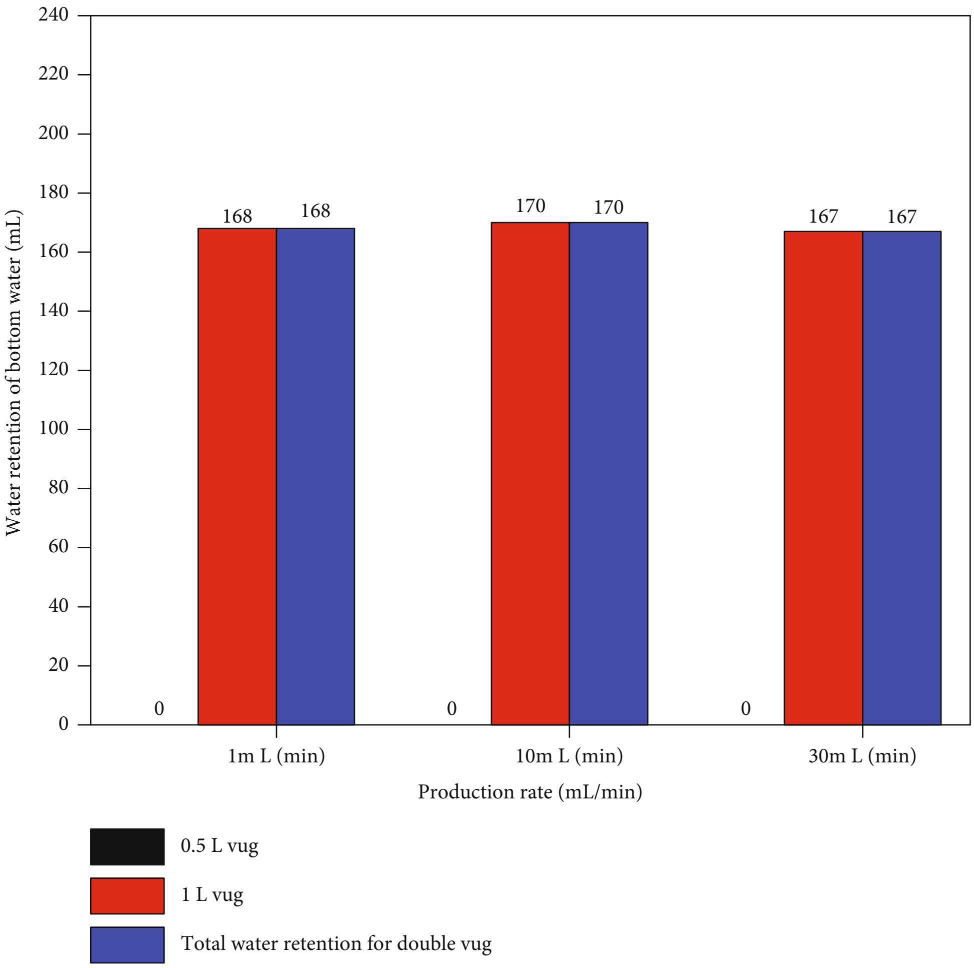


Figure 6: Column chart of bottom water invasion and retention in high-pressure physical property experiments under connection type I (different production rates).

production rate and bottom water type are considered, to ensure comparability real reservoirs [27–29].

Based on conventional models for fractured-vuggy reservoirs, in this paper, a high-pressure physical simulation experiment model for double-vug reservoirs with bottom water is designed. This model can be used for both simulating the bottom water conditions of real reservoirs and equating basic fracture-vug structures, reservoir characteristics, and field working systems of formations. The model is then used to test pressure variation curves and oil/water production variation curves under different bottom water types and production conditions, thus laying a foundation for clarifying development laws and calculating dynamic reserves of fractured-vuggy reservoirs with bottom water.

2. Experiments

2.1. Building a High-Pressure Physical Simulation Experiment Model for Double-Vug Reservoirs with Bottom Water. A 24 L high-pressure intermediate container was used to simulate bottom water. A 1 L intermediate container and a 0.5 L intermediate container (filled with carbonate cores and sediment) were used to simulate two vugs. Relying on simulated fracture generation with an unconsolidated sand pack, a high-pressure physical simulation experiment model was built for double-vug reservoirs with bottom water. The purpose was to explore how bottom water and fracture-vug relationship affect the characteristics of the "vug-fracture-vug" system in high-pressure physical property experiments. The permeability of the unconsolidated sand pack was 0.8-0.9 D, and the initial pressure of the model was 40 MPa. The schematic diagram of the connection relationship between vugs is shown in Figure 1. The pictures of high-pressure physical simulation experiment model for double-vug reservoirs with bottom water are shown in Figure 2. The difference between connection type I and II is the volume of the vug connected to the bottom water.

2.2. Experimental Methods. Experiments were performed to simulate a "vug-fracture-vug" double-vug reservoir with bottom water. Furthermore, the effects of bottom water, fracture-vug relationship, and oil recovery rate on the characteristics of the reservoir were explored in high-pressure physical property experiments.

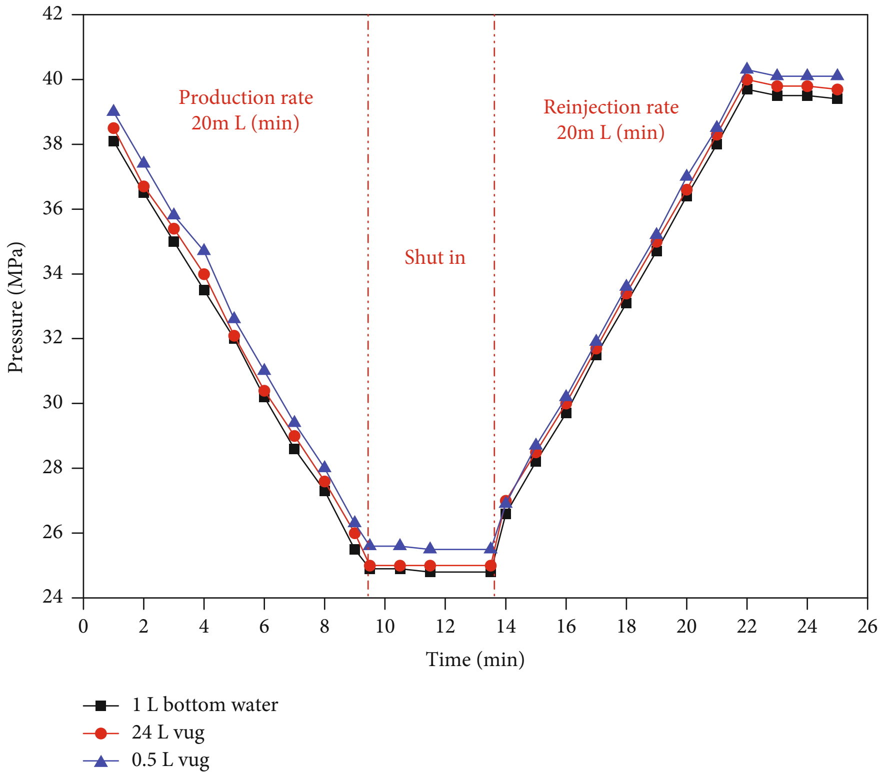


Figure 7: Pressure variation curves of reinjection in high-pressure physical property experiments under connection type I (production rate and reinjection rate = 20 mL/min).

2.2.1. *Experiments on Reservoirs with Constant-Volume Bottom Water*

(1) The 24 L intermediate container was filled with high-pressure water to simulate bottom water. The 1 L and 0.5 L intermediate containers were filled to simulate vugs. The 30 cm unconsolidated sand pack was filled for fracture simulation

(2) *Model Filling and Crude Oil Saturation*. After completing the model filling step, a vacuum pump was connected to evacuate the intermediate containers to a pressure of -0.09 MPa. Crude oil was connected to the containers at the bottom for oil saturation through self-priming until outflow of oil from the top. An ISCO pump was used to inject oil into the containers until a pressure of 25 MPa was reached. The containers were left to settle for 5 h for pressurized saturation. After pressure relief and discharge of bubbles, intermediate containers were separately injected with oil and pressurized to 40 MPa. The oil consumption of each process was recorded to calculate the initial crude oil saturation capacity of each vug. The original capacities of the 1 L and 0.5 L vugs in the experiments were 752.5 mL and 368.5 mL, respectively

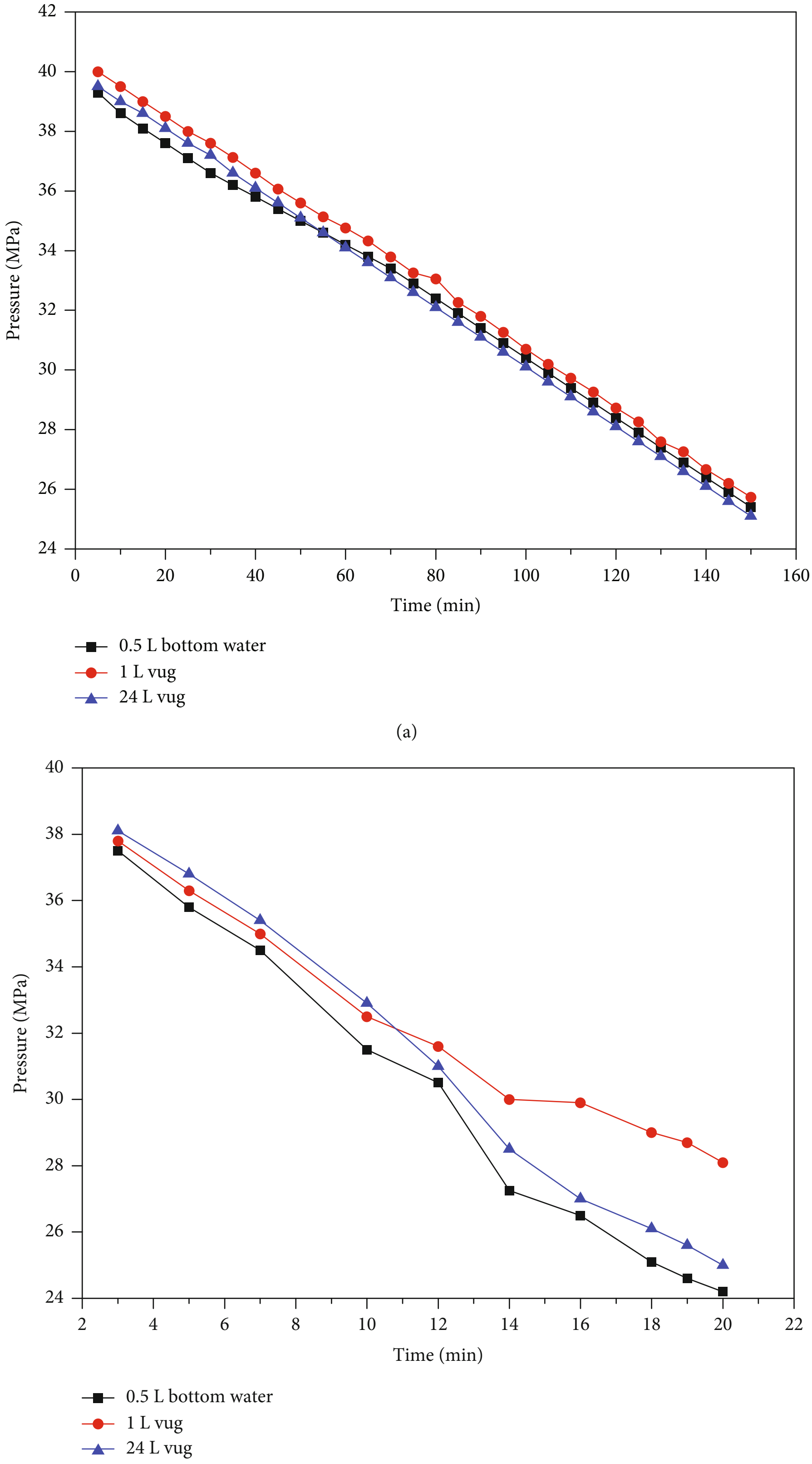
(3) Connection type I was adopted to build the high-pressure physical simulation experiment model for double-vug reservoirs with bottom water. Reduced-pressure production was conducted at the top of the 1 L intermediate container. Production proceeded at rates of 1 mL/min, 10 mL/min, 20 mL/min, and 30 mL/min and stopped when the pressure declined to 25 MPa. The variations of pressure, oil production, and water production in the production process were recorded. For connection type II, reduced-pressure production was conducted at the top of the 0.5 L intermediate container

(4) When the pressure had decreased to 25 MPa, the production valve was quickly closed, and the variations of the pressure buildups of the 24 L, 1 L, and 0.5 L intermediate containers were recorded over time

(5) Steps (1)-(3) were repeated. When the production pressure had decreased to 25 MPa, the valves at the two ends of the intermediate containers and the unconsolidated sand pack were closed, and the two immediate containers emptied. The residual oil contents in the containers were recorded to calculate the contributions of the two vugs to recovery percentage

2.2.2. *Experiments on Reservoirs with Constant-Pressure Bottom Water*

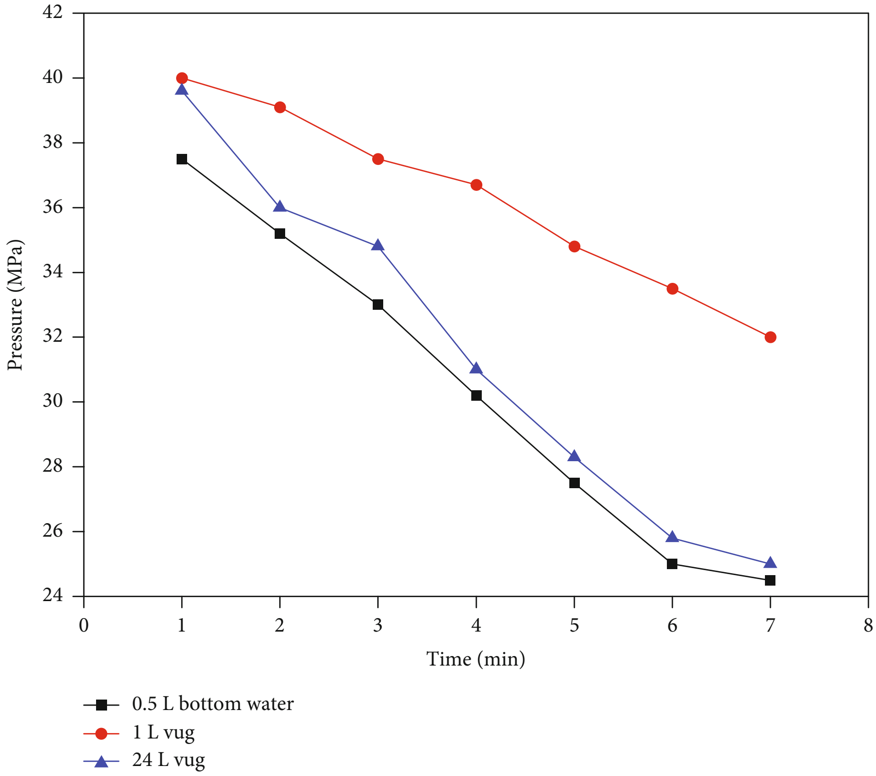
The same apparatus was used for experiments on reservoirs with constant-pressure bottom water and experiments on reservoirs with constant-volume bottom water. The difference between the two groups of experiments was that a constant-pressure pump was connected with a 24 L intermediate container containing bottom water to



(a)

(b)

Figure 8: Continued.



(c)

Figure 8: Pressure variation curves in high-pressure physical property experiments under connection type II (different production rates with (a) 1 mL/min, (b) 10 mL/min, and (c) 30 mL/min).

create the source of constant-pressure bottom water in experiments on reservoirs with constant-pressure bottom water.

(1) The 24 L intermediate container was filled with high-pressure water and connected to a 40 MPa constant-pressure pump to simulate constant-pressure bottom water. The 1 L and 0.5 L intermediate containers were filled to simulate vugs. The 30 cm unconsolidated sand pack was filled for fracture simulation

(2) *Model Filling and Crude Oil Saturation*. After completion of model filling, a vacuum pump was connected to evacuate the intermediate containers to a pressure of -0.09 MPa. Crude oil was connected to containers at the bottom for oil saturation through self-priming until outflow of oil at the top. An ISCO pump was used to inject oil into the containers until a pressure of 25 MPa was reached. The containers were left to settle for 5 h for pressurized saturation. After pressure relief and discharge of bubbles, intermediate containers were separately injected with oil and pressurized to 40 MPa. The oil consumption of each process was recorded to calculate the initial crude oil saturation capacity of each vug. The original capacities of the 1 L and 0.5 L vugs in the experiments were 834 mL and 413 mL, respectively

(3) Connection type I was adopted to build the high-pressure physical simulation experiment model for double-vug reservoirs with bottom water. Reduced-pressure production was conducted at the top of the 1 L intermediate container. Production proceeded at rates of 1 mL/min, 10 mL/min, and 20 mL/min and stopped when the water productivity of the outlet reached 98%. The variations of pressure, oil production, and water production in the production process were recorded. For connection type II, reduced-pressure production was conducted at the top of the 0.5 L intermediate container

(4) At the end of production, the valves at both ends of intermediate containers and the unconsolidated sand pack were closed, and the two vugs were emptied. The residual oil contents in the vugs were recorded to calculate the contributions of the two vugs to recovery percentage

3. Results and Discussions

3.1. High-Pressure Physical Property Experiments on Reservoirs with Constant-Volume Bottom Water

3.1.1. Production Characteristics under Connection Type I. A high-pressure physical simulation experiment model was built for “vug-fracture-vug” reservoirs with bottom water

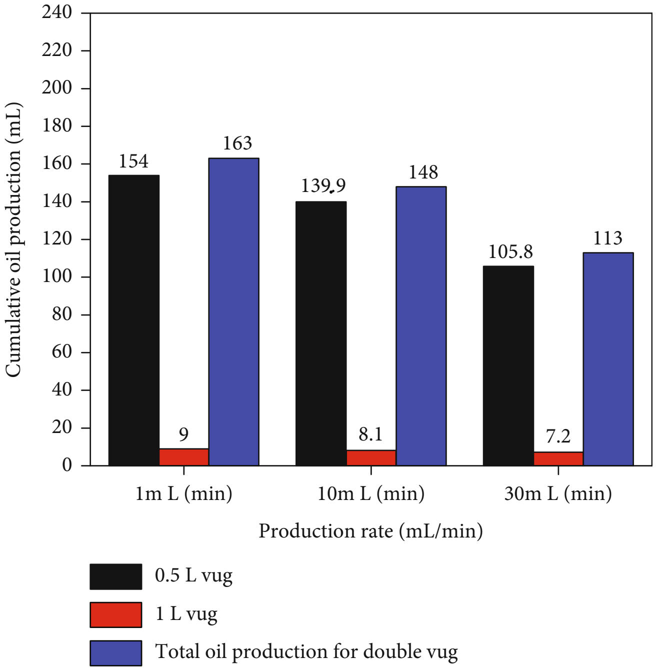


Figure 9: Column chart of cumulative oil production in high-pressure physical property experiments under connection type II (different production rates).

according to connection type I. Different production rates were adopted to assess the production characteristics of double-vug reservoirs with bottom water under different production rates, as shown in Figure 3.

Under connection type I, bottom water exerted a clear effect on the production pressure characteristics of double-vug reservoirs. Compared with vuggy reservoirs without bottom water, double-vug reservoirs with bottom water presented a clearly extended pressure drop time, suggesting that bottom water can significantly increase the natural energy of double-vug reservoir systems.

In addition, the production rate also affected the production characteristics of double-vug reservoirs with bottom water. At a production rate of ≤20 mL/min, the pressures of the 0.5 L vug, the 1 L vug, and the 24 L intermediate container containing bottom water all showed linear decreases. Production pressure differed little between various moments. When the production rate reached 30 mL/min, the pressure variation of the 0.5 L vug clearly differed from pressure variations of the 1 L vug and the 24 L intermediate container containing bottom water, showing a clearly moderated trend of pressure drop. Analysis showed that this phenomenon was mainly attributable to insufficient fracture flow capacity. That is, when the production rate exceeded 30 mL/min, the feed flow from the 0.5 L container to the output end was limited by the fracture, resulting in differences in pressure drop.

Figures 4 and 5 show that bottom water significantly affected the recovery percentage of double-vug reservoirs. Under connection type I, the recovery percentage of reservoirs with bottom water could reach about 16%, which is clearly higher than that of reservoirs without bottom water. Notably, no free water was produced at any stage of reservoir development. Therefore, under circumstances where the structural environment of the reservoir is not liable to water invasion or where there is no apparent water channeling under proper development, the presence of bottom water is conducive to reservoir development. Furthermore, it can provide sufficient energy for the development of fractured-vuggy reservoirs.

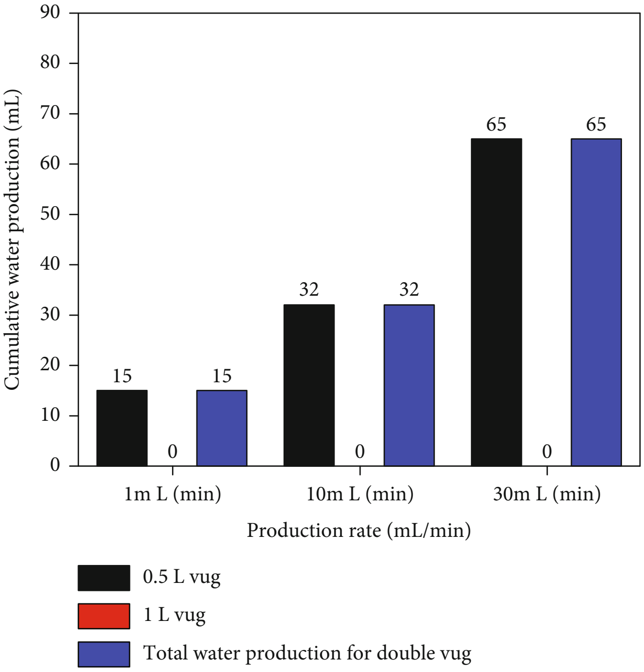


Figure 10: Column chart of cumulative water production in high-pressure physical property experiments under connection type II (different production rates).

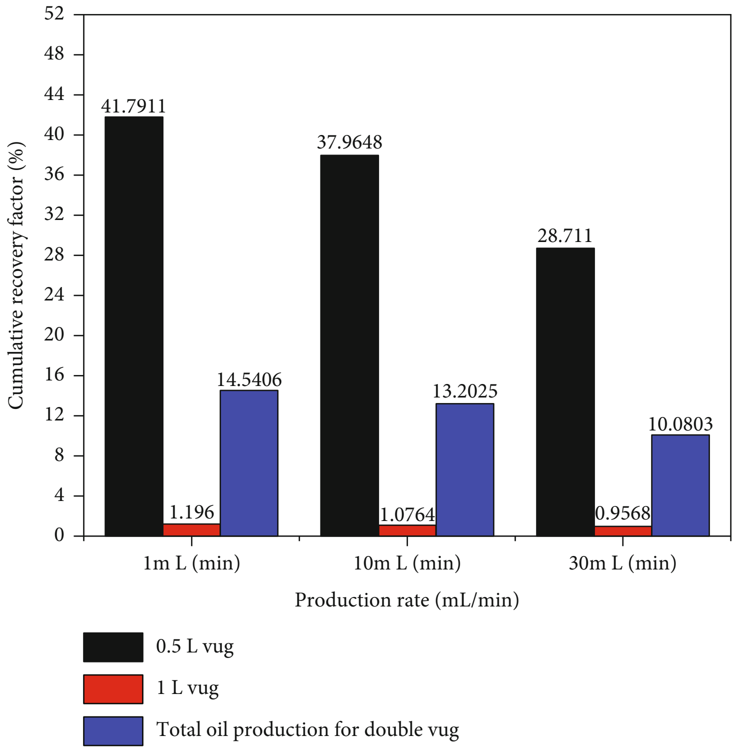


FIGURE 11: Column chart of cumulative recovery percent in high-pressure physical property experiments (different production rates).

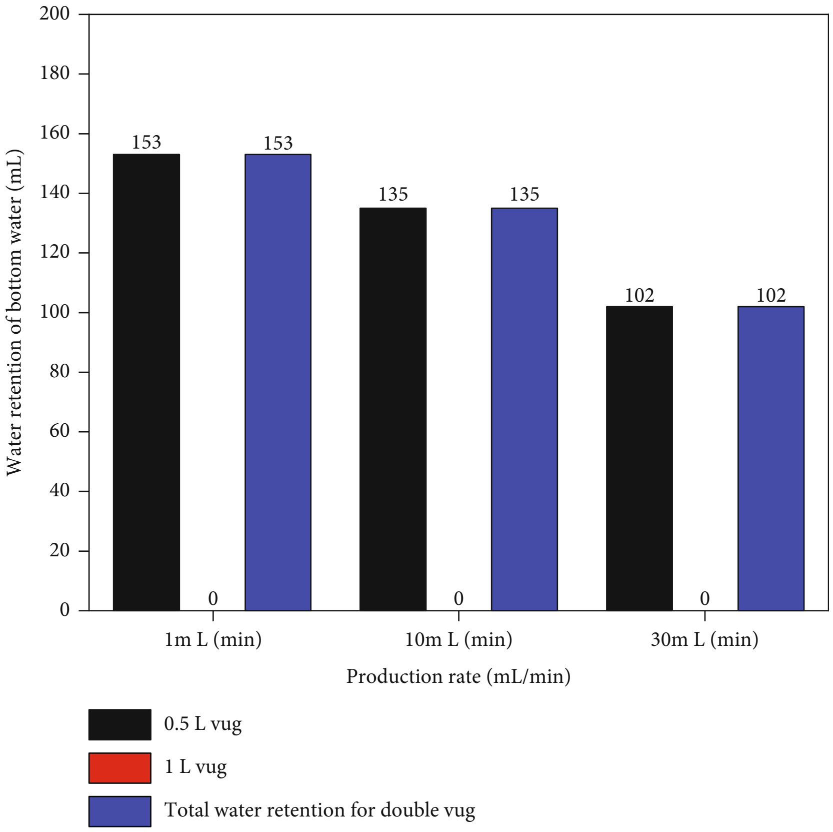
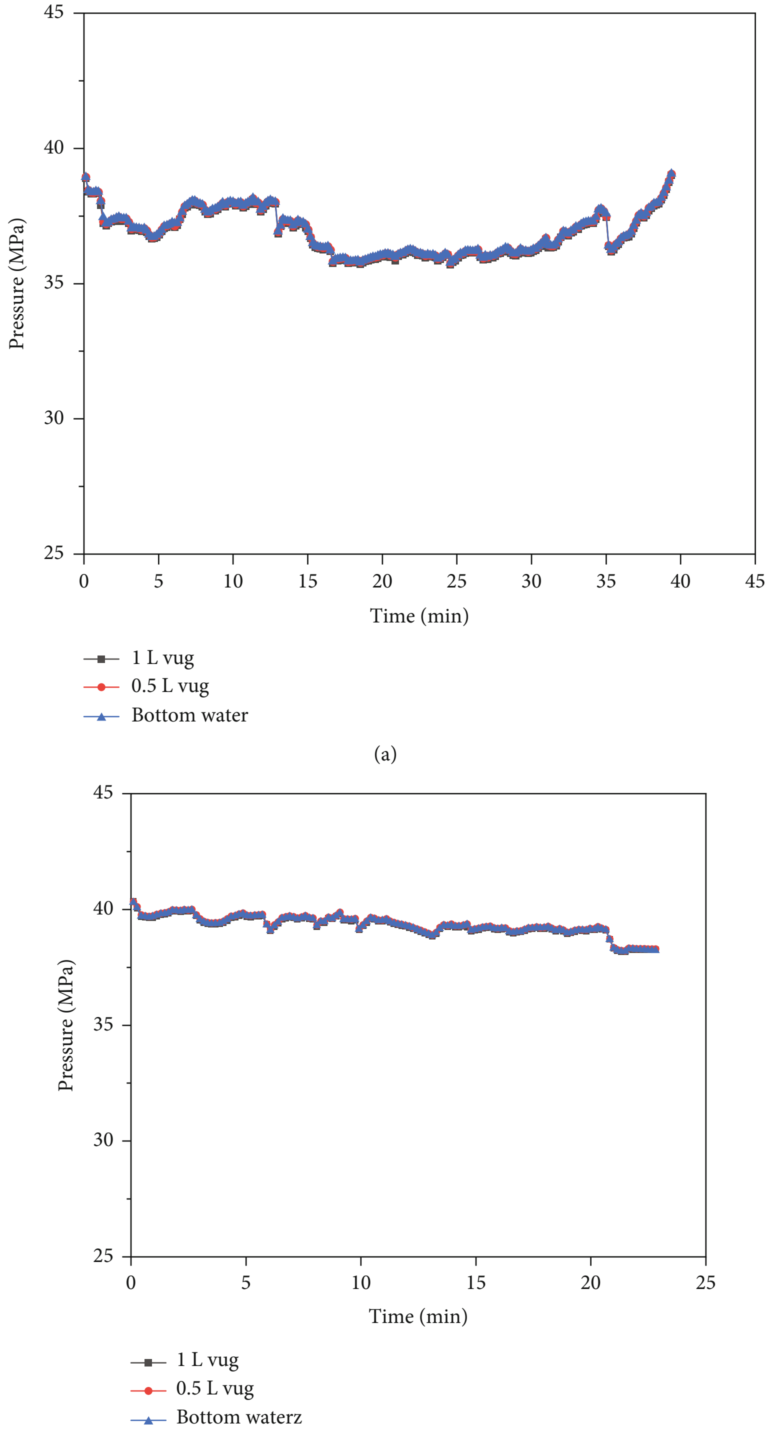


FIGURE 12: Column chart of bottom water invasion and retention in high-pressure physical property experiments under connection type II (different production rates).



(a)

(b)

Figure 13: Pressure variation curves for high-pressure physical property experiments on reservoirs with constant-pressure bottom water and production rate of 20 mL/min ((a) production well linked with 1 L vug and (b) production well linked with 0.5 L vug).

Within the range of assessed production rates, recovery percentages differed little between different experiments. This indicated that before water channeling, the production rate exerted little effect on the production of fractured-vuggy reservoirs. However, increasing production rate made it easier for bottom water to occur, which caused the rapid flooding of producing wells, and compromised the overall development effect of reservoirs.

According to Figure 6, bottom water mainly invaded the 1 L vug but did not intrude into the 0.5 L vug, which was consistent with the difference in oil production between both vugs. The 1 L vug experienced severe bottom water invasion,

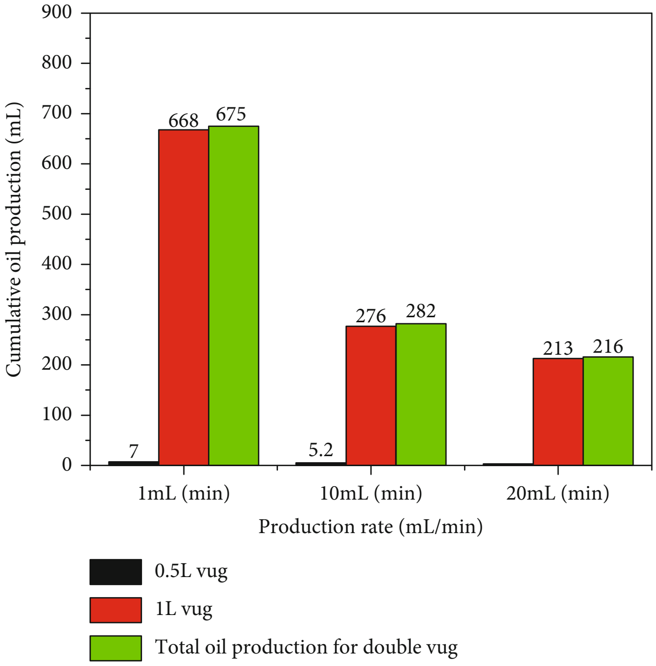


Figure 14: Column chart of cumulative oil production in high-pressure physical property experiments under connection type I (different production rates).

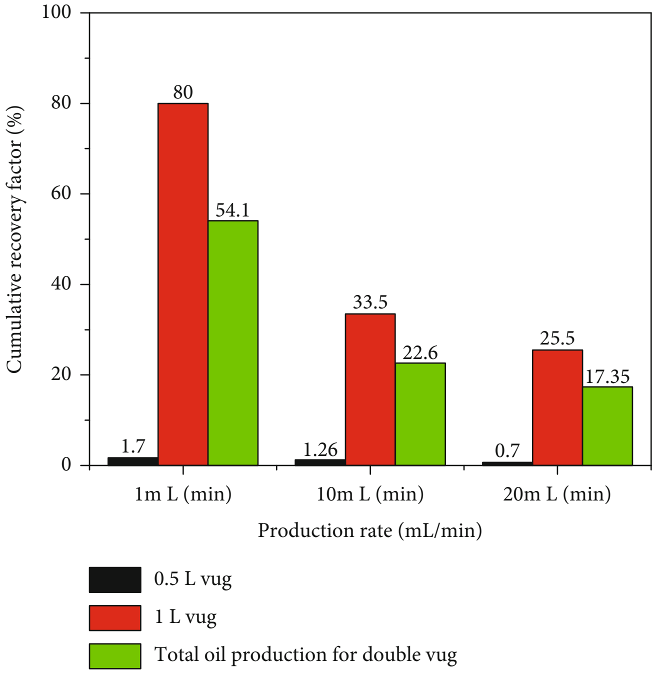


Figure 15: Column chart of crude oil recovery percent in high-pressure physical property experiments under connection type I (different production rates).

and its oil production was also significantly higher than that of the 0.5 L vug. Prior to water breakthrough at the output end, the bottom water invading vuggy reservoirs could displace crude oil and increase the production degree of crude oil in vugs. Therefore, bottom water can increase the natural energy of vuggy reservoirs and can be properly utilized to substantially improve the development effect of fractured-vuggy reservoirs.

Figure 7 shows the depletion pressure drop, pressure buildup, and injection pressure buildup curves of double-vug reservoirs with bottom water under connection type I. Here, production rate and injection rates were set to 20 mL/min.

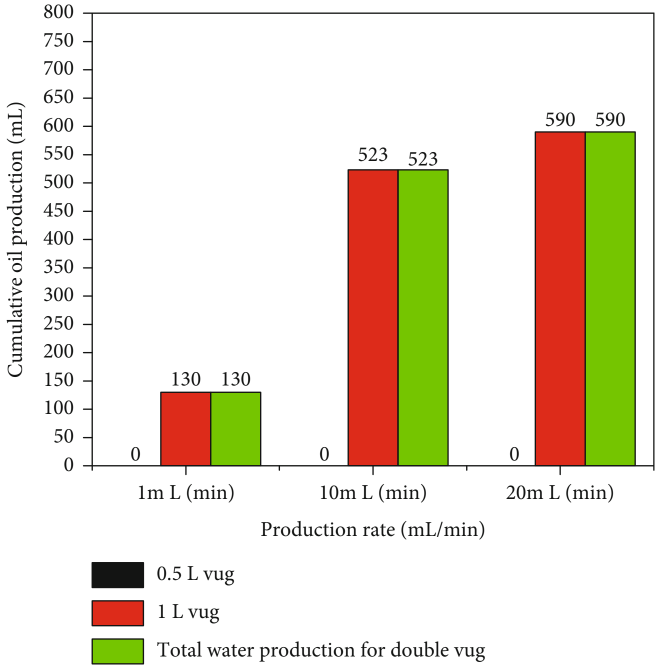


Figure 16: Column chart of cumulative water production in high-pressure physical property experiments under connection type I (different production rates).

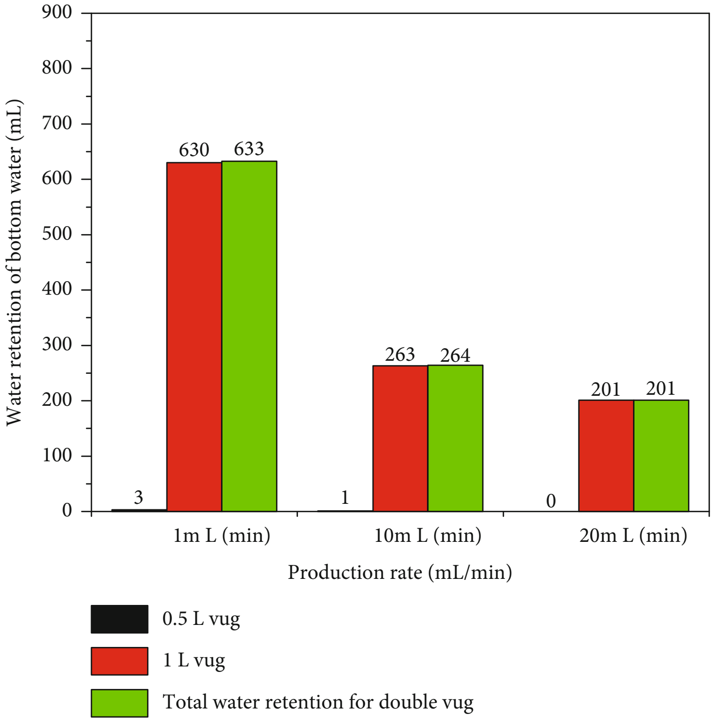
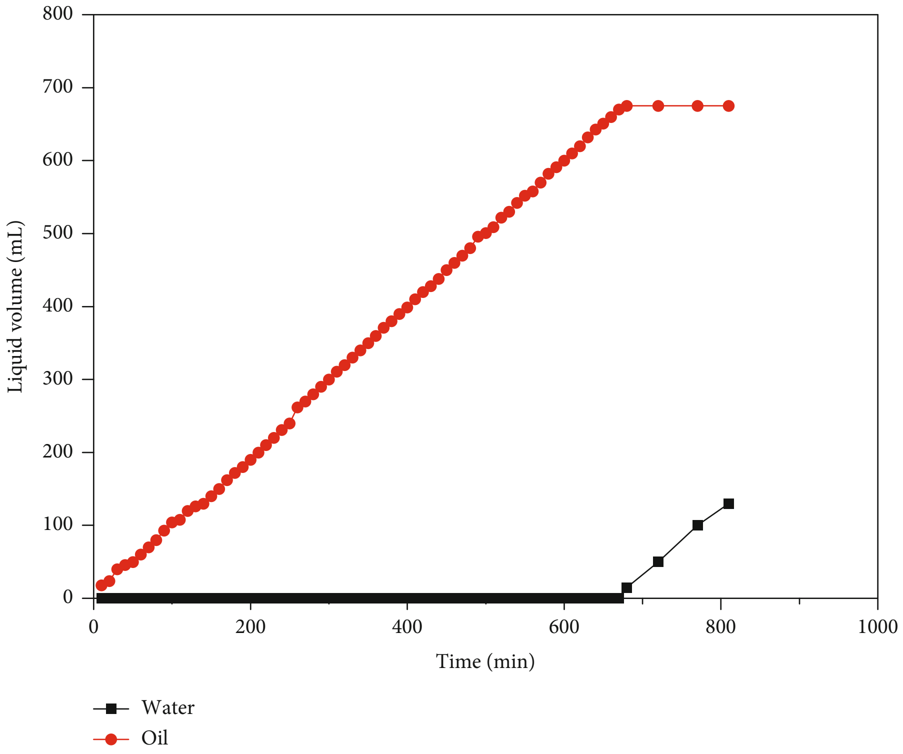


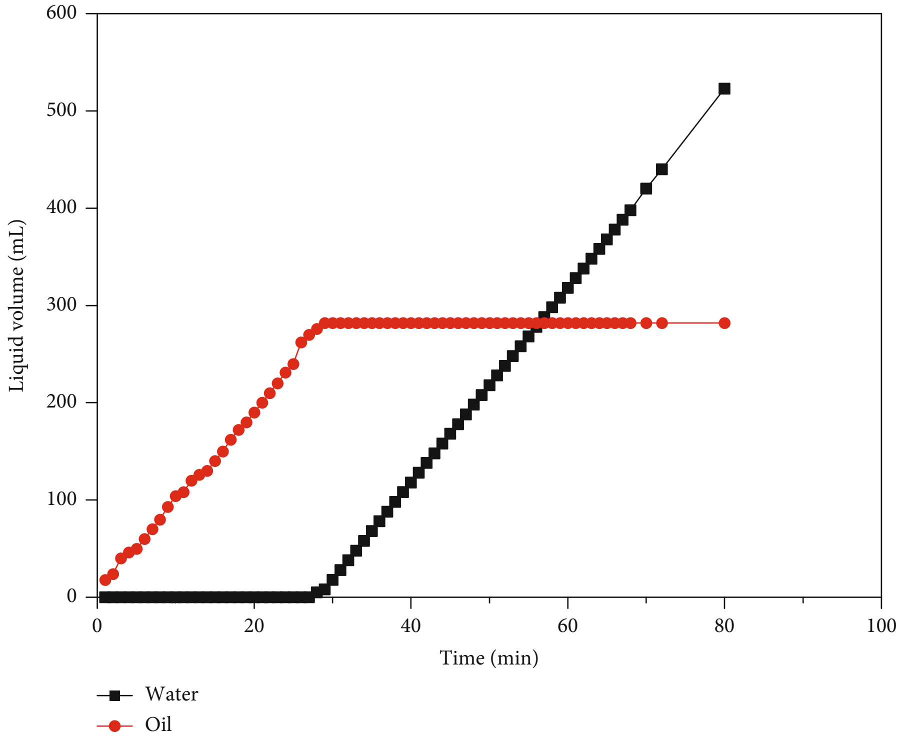
Figure 17: Column chart of bottom water invasion and retention in high-pressure physical property experiments under connection type I (different production rates).

The depletion pressure drop and injection pressure buildup curves both presented linear variations, implying that the fractures did not adversely impact fluid flow and that the fractured-vuggy reservoir could be put into stable production.

3.1.2. Production Characteristics under Connection Type II. A high-pressure physical simulation experiment model was built for "vug-fracture-vug" reservoirs with bottom water according to connection type II. Different production rates were adopted to assess the production characteristics of



(a)



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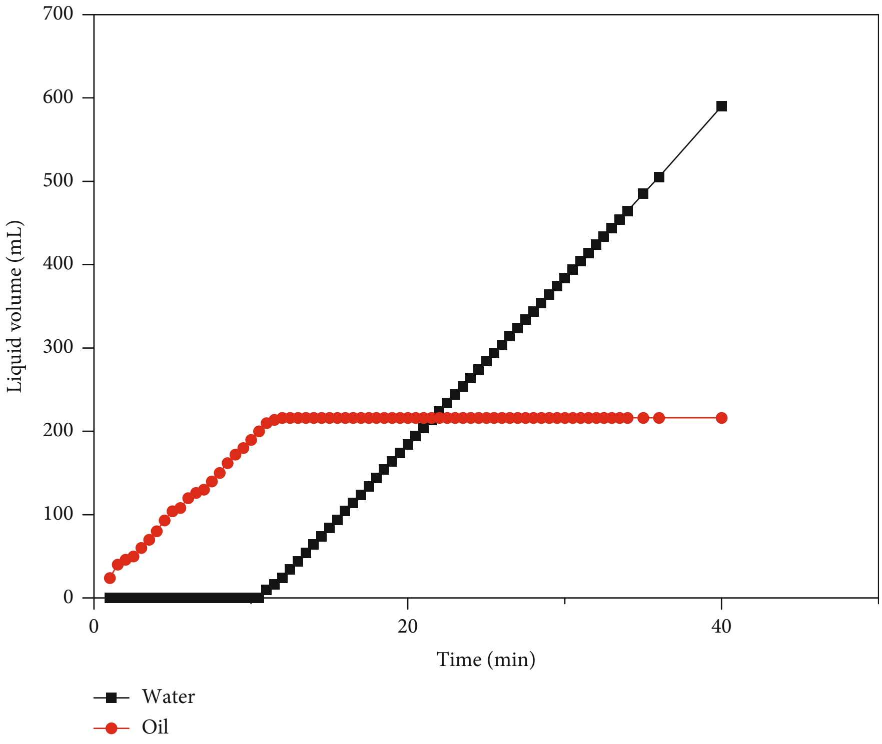


(c)

Figure 18: Oil/water production variation curves under connection type I (different production rates with (a) 1 mL/min, (b) 10 mL/min, and (c) 20 mL/min).

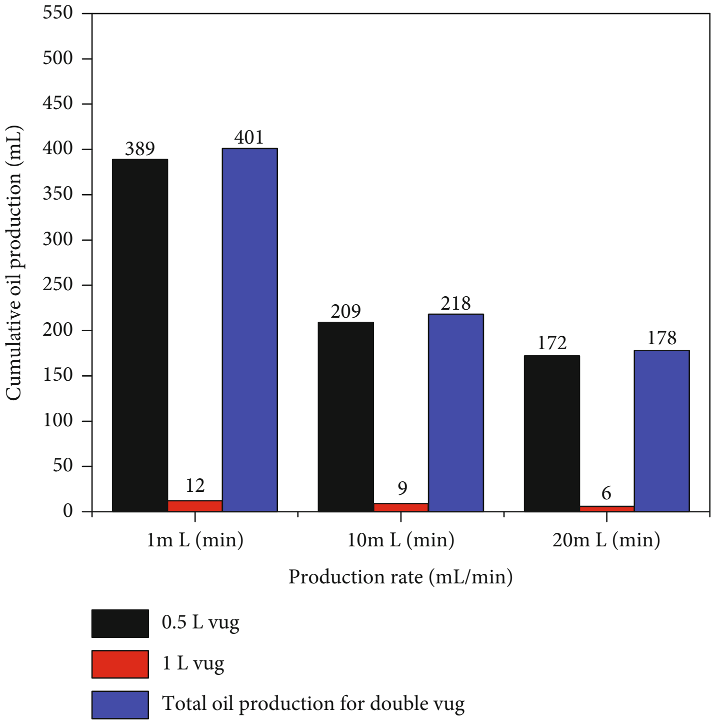


Figure 19: Column chart of cumulative oil production in high-pressure physical property experiments under connection type II (different production rates).

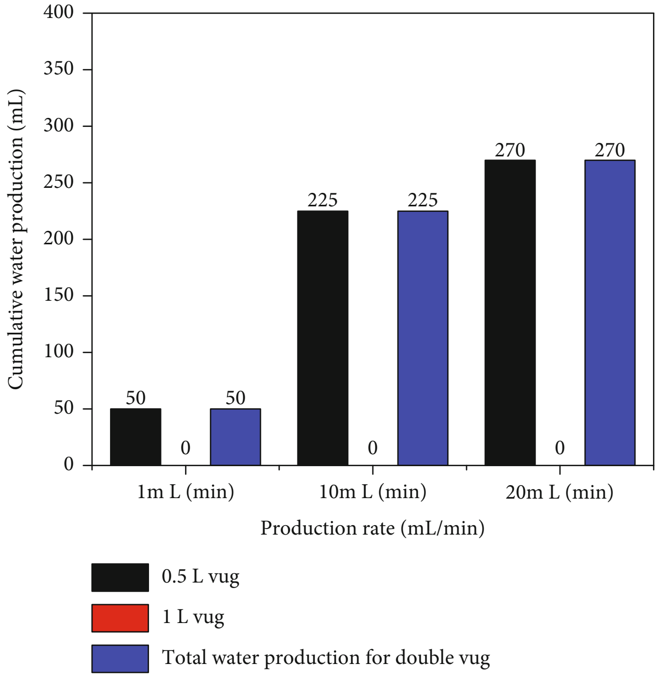


Figure 20: Column chart of cumulative water production in high-pressure physical property experiments under connection type II (different production rates).

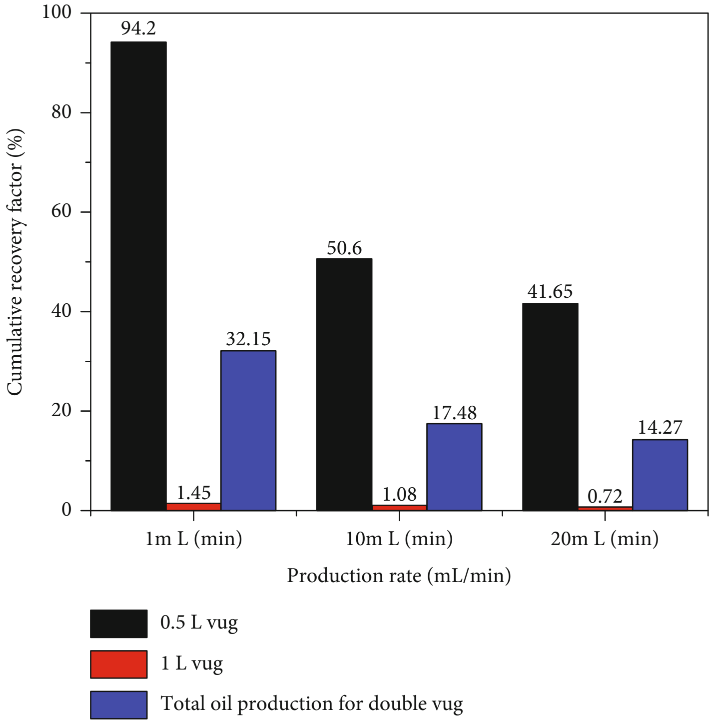


Figure 21: Column chart of crude oil recovery percentage in high-pressure physical property experiments under connection type II (different production rates).

double-vug reservoirs with bottom water under different production rates, as shown in Figure 8.

Under connection type II, production proceeded at the top of the 0.5 L vug, and the production rate clearly affected the production pressure characteristics of double-vug reservoirs with bottom water. At a production rate of 1 mL/min, the pressures of the 0.5 L vug, the 1 L vug, and the 24 L intermediate container containing bottom water all showed linear decreased. Production pressures differed little between various moments. When the production rate reached

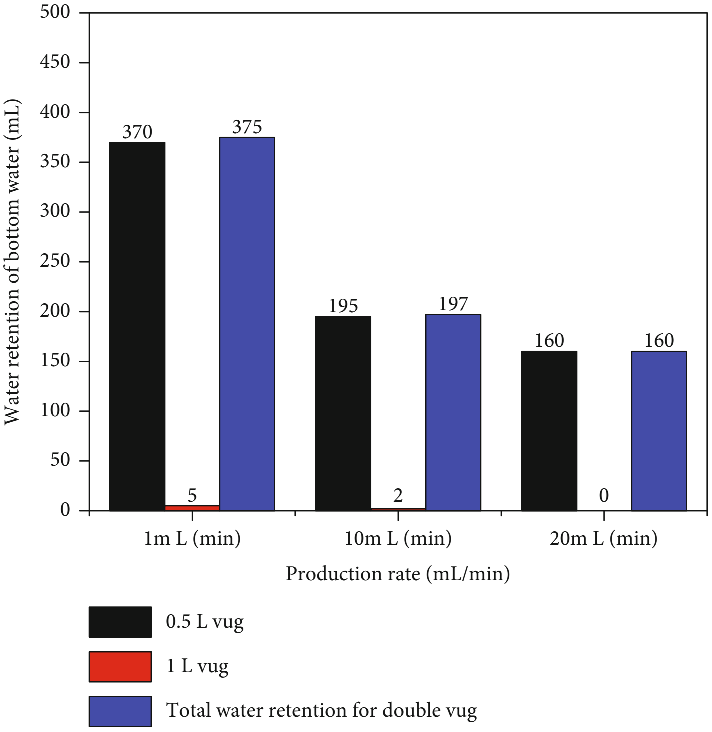


Figure 22: Column chart of bottom water invasion and retention in high-pressure physical property experiments under connection type II (different production rates).

10 mL/min, the pressure variation of the 1 L vug began to deviate from the pressure variations of the 1 L vug and the 24 L intermediate container containing bottom water, showing a clear moderated trend of pressure drop after 14 min of production. When the production rate reached 30 mL/min, the pressure variation of the 1 L vug clearly differed from the pressure variations of the 1 L vug and the 24 L intermediate container containing bottom water. Analysis showed that this phenomenon was mainly attributable to insufficient fracture flow capacity. That is, when the production rate exceeded 10 mL/min, the feed flow from the 1 L container to the output end was limited by the fracture, resulting in differences in pressure drop.

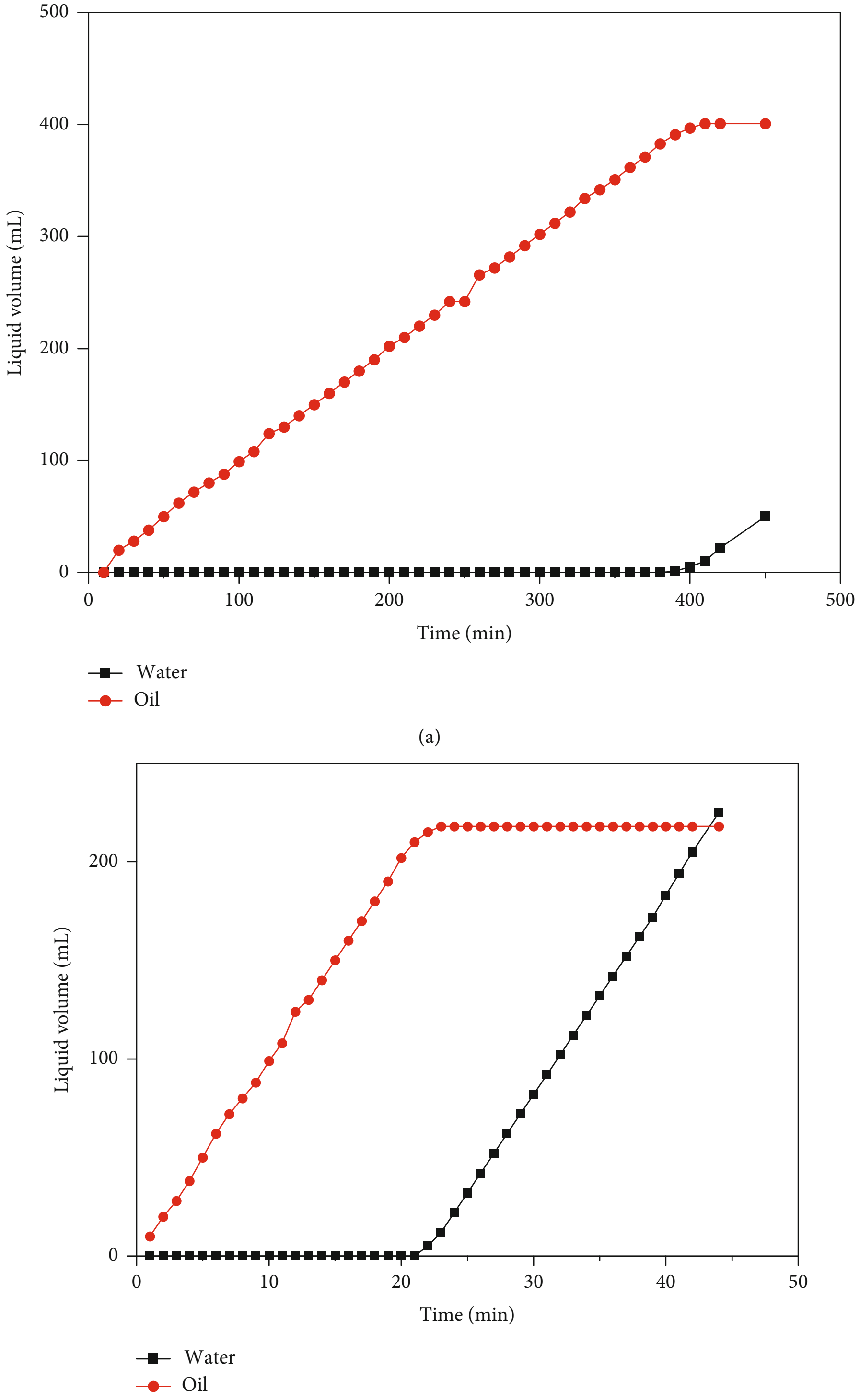
Figures 9–11 show that bottom water significantly affected the recovery percent of double-vug reservoirs. Under connection type II, the recovery percent of reservoirs with bottom water uniformly exceeded 10%, which is higher than that of reservoirs without bottom water. Moreover, bottom water channeling occurred in the production process of the 0.5 L vug at all three production rates, and increasing production rate led to higher water channeling volume and lower cumulative oil production of fractured-vuggy reservoirs. At a production rate of 1 mL/min, the water channeling volume was 15 mL, and the recovery percentage of the vug system was 14.5%. When the production rate increased to 10 mL/min, the water channeling volume was 32 mL, and the recovery percentage of the system was 13.2%. When the production rate further increased to 30 mL/min, the water channeling volume increased to 65 mL, and the recovery percentage of the system decreased to 10.1%. Thus, for reservoirs with bottom water which are susceptible to water channeling, the production rate should be properly controlled in the development process to avoid strong water channeling and fully utilize the elastic energy of bottom water for developing fractured-vuggy reservoirs.

According to Figure 12, bottom water mainly invaded the 0.5 L vug but did not intrude into the 1 L vug, which was consistent with the difference in oil production between the two vugs. The 0.5 L vug experienced substantial bottom water invasion, and its oil production was also significantly higher than that of the 1 L vug. With worsening bottom water channeling, the bottom water retention in vugs decreased, and the recovery percentage of reservoirs with bottom water decreased.

3.2. High-Pressure Physical Property Experiments on Reservoirs with Constant-Pressure Bottom Water

3.2.1. Production Pressure Variations. Figure 13 shows the pressure variation curves of high-pressure physical property experiments on reservoirs with constant-pressure bottom water under connection types I and II at a production rate of 20 mL/min.

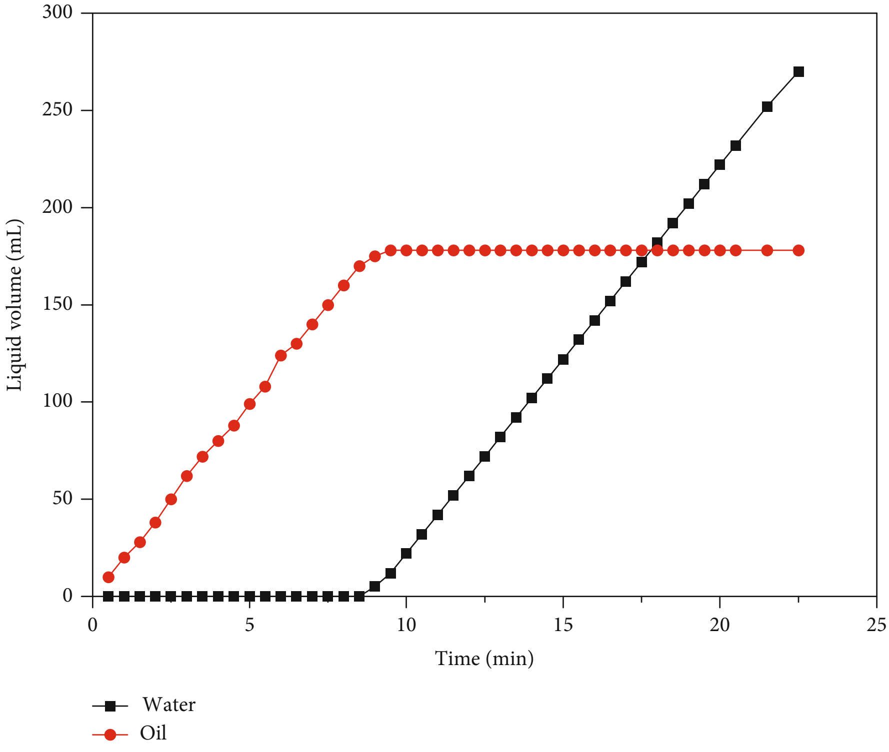
In experiments on reservoirs with constant-pressure bottom water, production pressure remained around 38-39 MPa with only slight fluctuation. Neither the production rate nor the fracture-vug relationship exerted any apparent effects on production pressure characteristics. Compared with reservoirs with constant-volume bottom water vuggy reservoir, vuggy reservoirs with constant-pressure bottom water had sufficient natural energy.



(a)

(b)

Figure 23: Continued.



(c)

Figure 23: Oil/water production variation curves under connection type II (different production rates with (a) 1 mL/min, (b) 10 mL/min, and (c) 20 mL/min).

3.2.2. Production Characteristics under Connection Type I. Figures 14–16 show that constant-pressure bottom water significantly affected the recovery percentage of double-vug reservoirs. Under connection type I, the recovery percentage of fractured-vuggy reservoirs with constant-pressure bottom water could uniformly exceed 17% at all three production rates. This is higher than that of fractured-vuggy reservoirs without bottom water and that of fractured-vuggy reservoirs with constant-volume bottom water. In particular, the recovery percentage of fractured-vuggy reservoirs with constant-pressure bottom water reached 54% at a production rate of 1 mL/min. The production rate significantly affected the development effect of fractured-vuggy reservoirs with constant-pressure bottom water. The recovery percentage at 1 mL/min was 3.13 times of that at 20 mL/min. The cumulative water production rates at 10 mL/min and 20 mL/min were far higher than that at 1 mL/min. Thus, given reasonable production systems, bottom water can provide sufficient energy for the development of fractured-vuggy reservoirs with constant-pressure bottom water, thus greatly improving their development effect. Under connection type I, most crude oil production was contributed by the 1 L vug, while the crude oil recovery percentage of the 0.5 L vug was uniformly lower than 1.7%.

According to Figure 17, bottom water mainly invaded the 1 L vug but only slightly intruded into the 0.5 L vug, which was consistent with the difference in oil production between these two vugs. The 1 L vug experienced substantial bottom water invasion and retention, and its oil production was significantly higher than that of the 0.5 L vug.

Figure 18 shows oil/water production variations over time for these experiments. After water breakthrough at the output end in case of fractured-vuggy reservoirs with constant-pressure bottom water, water productivity quickly increased to 100%, and further production basically produced no oil. Increasing the production rate led to shorter water breakthrough time and lower oil production upon water breakthrough.

3.2.3. Production Characteristics under Connection Type II. Figures 19–21 show that constant-pressure bottom water significantly affected the recovery percentage of double-vug reservoirs. Under connection type II, the recovery percentage of reservoirs with bottom water uniformly exceeded 14%.

From this figure, this is clearly higher than that of reservoirs without bottom water and reservoirs with constant-volume bottom water. Moreover, bottom water channeling occurred in the production process of the 0.5 L vug at all three production rates, and increasing the production rate led to higher water channeling volume and lower cumulative oil production of fractured-vuggy reservoirs. At a production rate of 1 mL/min, the water channeling volume was 50 mL, and the recovery percentage of the vug system was 32.2%. When the production rate increased to 10 mL/min, the water channeling volume increased to 225 mL, and the recovery percent of the system was 17.5%. When the production rate further increased to 20 mL/min, the water channeling volume was 270 mL, and the recovery percentage of the system decreased to 14.3%. Thus, regarding reservoirs with constant-pressure bottom water and sufficient energy, close attention should be paid to production rate control in the development process as this can avoid strong water channeling and fully utilize the elastic energy of bottom water for developing fractured-vuggy reservoirs.

According to Figure 22, bottom water mainly invaded the 0.5 L vug but only slightly intruded into the 1 L vug, which was consistent with the difference in oil production between both vugs. The 0.5 L vug experienced substantial bottom water invasion and retention, and its oil production was significantly higher than that of the 1 L vug. Moreover, with worsening bottom water channeling, the bottom water retention in vugs decreased, and the recovery percentage of reservoirs with bottom also water decreased.

Figure 23 shows oil/water production variations over time in experiments. A comprehensive analysis indicates that, compared with fractured-vuggy reservoirs with constant-volume bottom water, those with constant-pressure bottom water have more sufficient natural energy and greater development potentials. However, in practical development, reasonable production systems should be established to fully utilize the elastic energy of bottom water for developing fractured-vuggy reservoirs.

3.3. Comparison between High-Pressure Physical Property Experiments. For double-vug reservoirs with constant-pressure bottom water, the bottom water supplied during production can sustain energy supply to double-vug production, and pressure variations tend to be consistent. In the case of connection type I, the recovery percentage is higher, and bottom water mainly invades and retains in vugs based on open-well production. Because of water invasion and fracture limitation, production of distal reserves is restricted.

Compared with constant-volume bottom water, constant-pressure bottom water has sufficient energy and can quickly replenish vug energy. Therefore, the recovery percentage and bottom water invasion and retention volume of fractured-vuggy reservoirs with constant-pressure bottom water are both higher than those of fractured-vuggy reservoirs with constant-volume bottom water.

4. Conclusions

(1) Bottom water clearly affects the production pressure characteristics of double-vug reservoirs. Compared with vuggy reservoirs without bottom water, double-vug reservoirs with bottom water have a clearly extended pressure drop time, suggesting that bottom water can significantly increase the natural energy of double-vug reservoir systems

(2) In circumstances where the structural environment of the reservoir is not liable to water invasion or where there is no obvious water channeling under proper development, the presence of bottom water is conducive to reservoir development and can provide sufficient energy for the development of fractured-vuggy reservoirs. Bottom water can be utilized to substantially improve the development effect of fractured-vuggy reservoirs

(3) Worsened bottom water channeling leads to less bottom water retention in vugs and a lower recovery percentage of reservoirs with bottom water. For reservoirs with bottom water which are susceptible to water channeling, the production rate should be appropriately controlled in the development process to avoid strong water channeling. Furthermore, the elastic energy of bottom water should be fully utilized for developing fractured-vuggy reservoirs

(4) For double-vug reservoirs with constant-pressure bottom water, the bottom water supplied during production can sustain energy supply to double-vug production, and pressure variations tend to be consistent. In the case of large vugs, the recovery percentage is higher, and bottom water mainly invades and retains in vugs based on open-well production. Because of water invasion and fracture limitation, production of distal reserves is restricted

(5) Compared with constant-volume bottom water, constant-pressure bottom water has sufficient energy and can quickly replenish vug energy. Therefore, the recovery percentage and bottom water invasion and retention volume of fractured-vuggy reservoirs with constant-pressure bottom water are both higher than those of fractured-vuggy reservoirs with constant-volume bottom water

Data Availability

We checked it carefully and confirmed that all data, models, and code generated at the manuscript could be obtained from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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