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ORIGINAL ARTICLE

Experimental study on water invasion mechanism of fractured carbonate gas reservoirs in Longwangmiao Formation, Moxi block, Sichuan Basin

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Abstract
Fractured carbonate gas reservoirs feature high heterogeneity and difficulty in development, and the invasion of edge and bottom water intensifies the complexity of exploitation of such gas reservoirs. In this study, reservoir cores with a permeability of 0.001 mD, 0.1 mD, and 10 mD were selected by analyzing the fracture characteristics of the Longwangmiao gas reservoir, and water invasion in fractured carbonate gas reservoirs with edge and bottom water was simulated using an experimental system to investigate the effects of different parameters on gas reservoir exploitation. The results show that the larger the water volume ratio, the more serious the water invasion and the lower the recovery factor. But water aquifer did not strongly affect the recovery factor once the water aquifer exceeded a critical value. The higher the gas production rate, the faster the water invasion and the smaller the recovery factor. The recovery factor peaked when the gas production rate was equivalent to the gas supply capacity of the matrix to the fractures. For gas reservoirs with the overall permeability, the higher the matrix permeability, the higher the recovery factor. Although an appropriate fracturing scale was able to enhance the recovery factor when its matrix permeability was low, an excessive fracturing scale would cause water to flow along the fractures at a rapid rate, which further caused a sharp decline in the recovery factor. With the increase of matrix permeability, fractures exerted a decreasing effect on gas reservoirs. These results can provide insights into a better understanding of water invasion and the effects of reservoir properties so as to optimize gas production in fractured carbonate gas reservoirs.

Keywords Fractured carbonate gas reservoirs · Physical simulation · Water volume ratio · Matrix permeability · Recovery factor · Water influx

Introduction

As an important gas reservoir, fractured gas reservoir plays a significant important role among developed gas reservoirs, such as the Dina, Keshen, and Dabei gas reservoirs in Tarim Basin, Longwangmiao and Gaoshiti gas reservoirs in Sichuan Basin (Li et al. 2017a, 2018). The gas reservoirs are characterized by low permeability in matrix, well-developed fractures, complex fracture distribution, high heterogeneity and active edge-bottom water (Shen et al. 2014a; Li et al. 2018). The reservoir pressure will gradually decrease with the exploitation of gas reservoirs, and the edge and bottom water will invade the gas-bearing areas under the action of pressure potential, which leads to water–gas two-phase filtration and reduces gas phase filtration capability and deliverability of individual wells (Shen et al. 2015; Rezaee et al. 2013). The edge and bottom water invades the well bottom with the increasing of water invasion, whereas with

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a steep increase in the wellbore liquid level and increase of abandonment pressure, a large amount of gas in the reservoirs will be trapped, which results in the lower recovery factor of gas reservoirs. According to previous studies, the recovery factor of water-driven gas reservoirs (20–60%) is significantly lower than that of dry gas reservoirs (80–95%) (Li et al. 2010, 2017b; Cheng et al. 2017). Moreover, the operations such as draining are required when the gas-phase superficial velocity in the wellbore is too low to provide sufficient energy to remove accumulated liquid from the well bottom, which increases the production costs. So, the edge and bottom water invasion not only results in a lower recovery factor of gas reservoirs, but it also increases production difficulty and the production cost of individual wells (Zou 2016; Yang et al. 2017). Therefore, there is of great significance to identify the essence of the invasion mechanism of gas reservoirs with active edge and bottom water, which directly relate to the efficient and reasonable development of the gas reservoirs.

The problem of water invasion in gas reservoirs has always been one of the major concerns in terms of productivity, increased operating costs and environmental effects (Shen et al. 2015). Some micro-physical model experiments on water invasion into gas reservoirs have been conducted and its impact on gas productivity has been considered over the past years. Persoff and Pruess (1995), Chen et al. (2013), Zhou et al. (2002) and Li et al. (2008) developed a transparent micro-physical model of a water-driven gas experiment by etching a pore throat structure on a glass panel using laser etching technology, and they argued that water trapped the gas in the matrix block by means of circumfluence, cut off phenomenon and water lock, which resulted in a reduction of both gas production rate and recovery factor. Jiao et al. (2014) and Fang et al. (2017) conducted the full-diameter cores and analyzed the influence of different factors on water invasion in gas reservoirs with the pore type. Ahmadi et al. (2014) predicted water breakthrough time by calculating the time of water-cone breakthrough, which was applied in heterogeneous sandstone gas reservoirs. Based on the dynamic monitoring data of gas wells collected close to the frontal area of water invasion, Feng et al. (2013) and Li et al. (2017c) studied the local water invasion mechanism of gas reservoirs. Moreover, Shen et al. (2014b) and Lies (2000) conducted the effects of reservoir characteristics on water cones with the numerical simulation. Kabir et al. (2015, 2016), Patacchini (2017) and Wang et al. (2017) predicted the intensity of water invasion and water rate using the matter balance equation combined with production data. Deng et al. (2018) studied the influence of unified strength theory on loess using physical experiment and numerical simulations. Although there were lots of research work conducted on the water invasion in gas reservoirs, water invasion of gas reservoirs was not fully perceived at present, especially in fractured gas reservoirs. Thus, it is extremely necessary to understand the reservoir characteristics and the water invasion mechanism in fractured gas reservoirs, which provides a basis for the efficient development of gas reservoirs.

In this study, the experimental system of water invasion in gas reservoirs with the edge-and-bottom aquifer was established, and the matrix cores with different permeabilities were selected based on the reservoir characteristics of Longwangmiao Formation, Moxi block, in Sichuan Basin, China. The fracture core samples generated by artificial fracturing were designed and the experimental simulation of water invasion in fractured gas reservoirs were conducted to understand the flow mechanism. Then the effects of the related reservoir properties and production parameters with different bottom water volume ratios, gas production rates, matrix permeability, and fracture apertures on gas production were studied. These results can provide a better experimental evidence of water invasion for improving the gas recovery and efficient exploitation in fractured gas reservoirs.

Characteristics of the gas reservoir

The gas reservoir of Longwangmiao Formation, Moxi block is located in Suining, Ziyang, Chongqing and Tongnan of Sichuan Basin, China, which belongs to the Weiyuan-Longnvsi structure group of Central Sichuan gentle fold bet shown in Fig. 1 (Li et al. 2017a, 2018). And it is a super-giant marine-facies integral carbonate gas reservoir of the largest single scale discovered in China, which has proved gas reserves of over 4400×10^8 m^3 (Li et al. 2017b). It is a fractured-porous reservoir whose average formation pressure, pressure coefficient, average formation temperature, and geothermal gradient are 75.83 MPa, 1.64, 141.3 °C

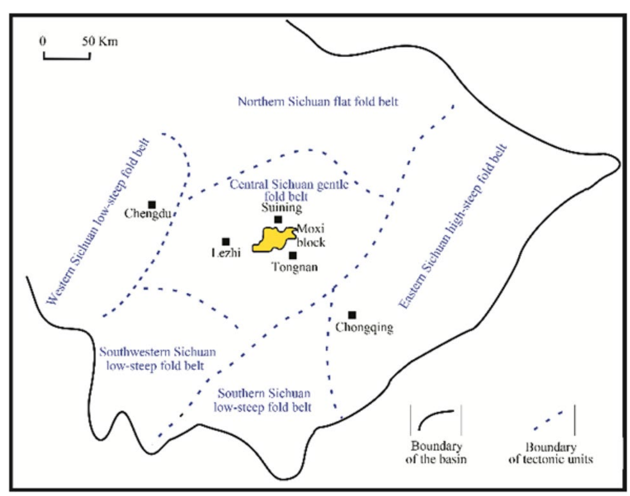


Fig. 1 Location of Longwangmiao Formation, Moxi block in Sichuan Basin, China

and 2.3 °C/100 m, respectively. According to the statistical analysis of the full-diameter core samples collected in the block, the porosity ranges from 2.48 to 6.05% and is 4.81% on average, and the permeability is distributed mainly in 0.0101 mD and 78.55 mD and is 4.751 mD on average. By the end of August, 2017, the proven total reserves of natural gas had reached 440.385×10^9 m^3, and a total number of 44 wells had been brought into production. The cumulative gas output was 242.36×10^8 m^3 and the individual well production allocation was 64.3×10^4 m^3. On the whole, the gas reservoir in Longwangmiao Formation has large reserves and high individual-well production, but some gas wells located in the structurally low region with well-developed reservoir fractures are vulnerable to rapid production decline and a high risk of water invasion. So far there are 13 wells which have been found to produce water. The wells that have higher water production, such as MX204, 009-3-X2, and 009-3-X3, are increasingly severely affected by water invasion.

The filtration characteristics and water invasion performance of gas reservoirs are directly correlated with fracture morphology, occurrence, and filling features, etc. Thus, a morphological description, micro-resistivity imaging logging, fracture statistics, and a permeability test were performed for cores collected from different wells in the area, and the morphological characteristics of fractures were also investigated. In the study, the cores of wells MX12, MX13, MX16, MX17, MX19, MX20, MX202, and MX204 in the gas reservoir of Longwangmiao Formation, Moxi block, were selected for the morphological description and micro-resistivity imaging logging, which indicated that there were mainly tectonic fractures, horizontal fractures, and suture lines that developed in the gas reservoir. Some fractures were filled with pitch and dolomite, as shown in Table 1. Statistical analysis of fractures with apertures > 0.1 mm, as illustrated in Fig. 2, suggested a significant difference between fracture densities in

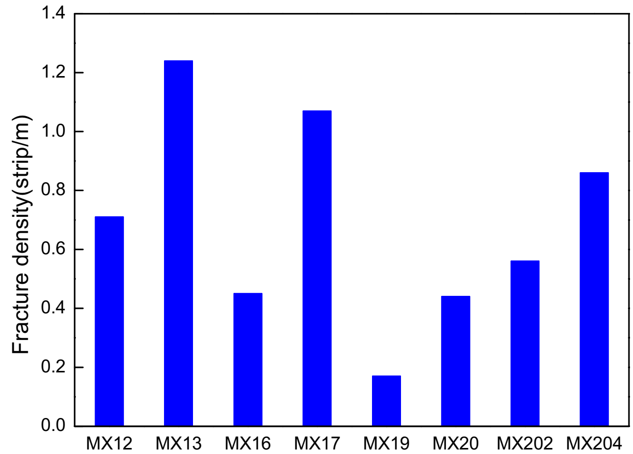
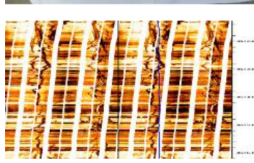
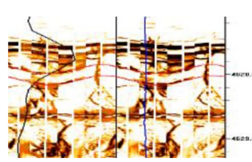
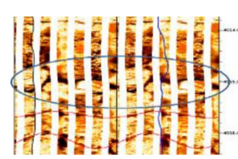


Fig. 2 Histogram of fracture density of reservoir cores in Longwangmiao formation

different areas, and the fracture density ranged from 0.17 to 1.24/m and averaged 0.69/m. Moreover, fractures were widely distributed in wells MX13, MX17, and MX204.

To identify the influence of fractures on reservoir permeability, 1300 plunger samples and 100 full-diameter cores from different wells in the gas reservoir of Longwangmiao Formation were selected for statistical analysis, as shown in Fig. 3. As full-diameter cores were larger than plunger samples and contained more information of gas reservoirs. Since the permeability of plunger samples was closer to the matrix permeability while that of full-diameter cores was closer to the actual permeability of the reservoirs. According to the statistical results, the permeability of full-diameter core samples (the average permeability was 4.751 mD) was greater than that of plunger samples (the average permeability was 0.996 mD), which indicated that fractures were well developed in gas reservoirs of Longwangmiao Formation, Moxi block.

Table 1 Reservoir fracture types of Longwangmiao formation in Moxi block

Fracture type	Tectonic fracture	Horizontal fracture	Suture line
Representative core samples			
Micro-resistivity image logging			
Fracture filling	Partially filled with dolomite	Half-filled with dolomite	Filled with mud or pyrite

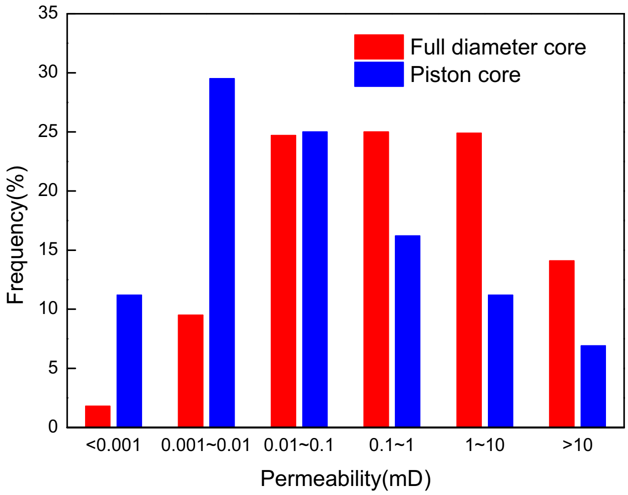


Fig. 3 Permeability frequency of reservoir cores in Longwangmiao formation

Experimental samples and methods

Experimental samples

In the previous studies, typically one longitudinal fracture was emerged in the cores to simulate the fractured gas reservoir. Although the method was simple, it differs significantly from the complex occurrence and distribution of fractures formed in geological conditions. Thus, the porous cores with original permeability values of 0.001 mD, 0.1 mD, and 10 mD were selected to accurately characterize the mechanism of edge and bottom water invasion in fractured gas reservoir and to simulate the complex distribution of fractures in the gas reservoir conditions. A creep machine was used to slowly apply shear stress to the cores, which were then deformed with irregular micro-fractures generated on their surface and inside. The permeability increased by 10–100 times compared with the original permeability, and then the experiments of micro-fracture gas reservoirs were conducted. Once again, the stress was applied to the cores using the creep machine to create larger fractures and longitudinal raptures, which were filled with the proppant. The permeability further increased by more than 100–10,000 times, and the experiments of macro-fracture gas reservoirs were carried out. The basic properties of carbonate core samples used in this study were shown in Table 2.

Experimental methods

In the study, the experimental system of water invasion in fractured carbonate gas reservoirs was shown in Fig. 4. High-purity nitrogen served as the natural gas under reservoir conditions. Intermediate containers of different volumes were filled with lab-prepared standard formation water with a density of 80,000 mg/L to simulate the formation water. Quantitative natural depletion was used, i.e., exploiting the gas at a constant gas production speed by regulating the valve at the outlet end during the initial stage. Gas and water were separated by a gas–liquid separator to measure water yield and gas yield when the front of the water invasion reached the outlet end of the experimental model. Some meters, including pressure sensors and flowmeters, were used to record the pressure and flux during the whole experiment to analyze the water invasion at different periods (Table 3).

The following experiments were set up to simulate the water invasion mechanism of fractured gas reservoirs under different conditions: (1) to simulate the influence of the water volume (aquifer size) on the water invasion mechanism, an experiment where the permeability of the fractured cores was 0.1 mD, the gas production rate was 1000 mL/min, and the bottom pressure was 30 MPa was carried out at the aquifer of 0, 3, 7, 12, and infinity times in size; (2) to simulate the influence of different gas production rates on the water invasion mechanism, an

Table 2 Basic properties of carbonate core samples used in this study

Core no.	Core type	Core size (cm) (length × diameter)	Porosity (%)	Permeability (mD)	Core classifications
1	Porous	15.15 × 10.02	3.2	0.0011	Class I
2	Micro-fractured		3.5	0.01	
3	Fractured (filled with proppant)		4.1	10	
4	Porous	14.98 × 10.12	6.0	0.1	Class II
5	Micro-fractured		6.3	10	
6	Fractured (filled with proppant)		6.7	100	
7	Porous	15.06 × 10.23	10.1	10	Class III
8	Micro-fractured		10.3	215	
9	Fractured (filled with proppant)		10.5	1500	

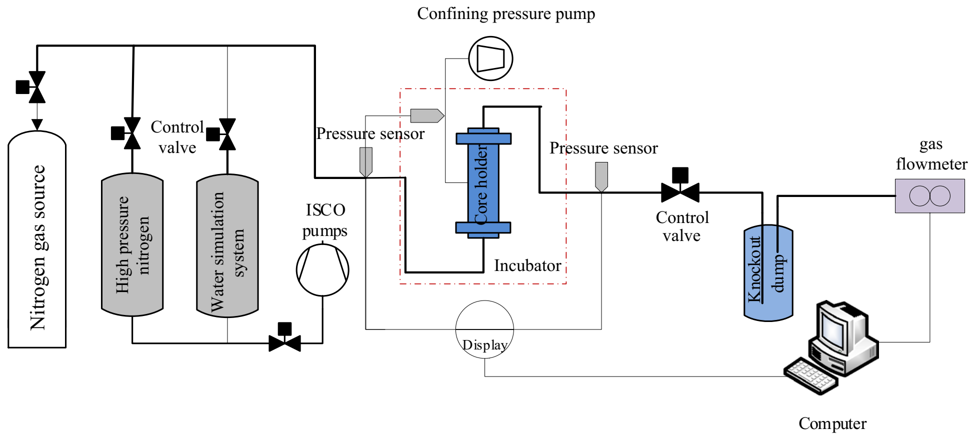


Fig. 4 Experimental system of water invasion in fractured carbonate gas reservoirs

Table 3 Different experiments of water invasion conducted in this study

Experimental scheme	Core no.	Gas production rate (mL/min)	Aquifer size (pv)
Different aquifer sizes	2	1000	0, 3, 7, 12, infinity
Different gas production rates	2	500, 1000, 2000, 4000	7
Different matrix permeabilities	3, 5, 7	1000	7
Different fracture apertures	1, 2, 3, 4, 5, 6, 7, 8, 9	1000	7

experiment where the aquifer size was 7 times and the bottom pressure was 30 MPa was conducted at gas production rates of 500 mL/min, 1000 mL/min, 2000 mL/min, and 4000 mL/min; (3) to simulate the influence of different matrix permeabilities on the water invasion mechanism, an experiment where the aquifer was 7 times, the bottom pressure was 30 MPa, and the gas production rate was 1000 mL/min was conducted on cores 3, 5, and 7 with similar permeability; (4) to simulate the influence of different fracture apertures on the water invasion mechanism, an experiment where the aquifer was 7 times in size, the bottom pressure was 30 MPa, and the gas production rate was 1000 mL/min was carried out on cores with a matrix permeability of 0.001 mD, 0.1 mD, and 10 mD after different scales of fractures were created by artificial fracturing.

Results and discussion

To understand the water invasion mechanism of fractured gas reservoirs and provide the theoretical evidence of gas reservoir exploitation and evaluation, effects of the related reservoir properties and production parameters such as aquifer sizes, gas production rates, matrix permeabilities, and fracture apertures on gas reservoirs with water invasion were investigated by simulating the development process of fractured gas reservoirs with active edge and bottom water.

Different aquifer sizes

There were formation aquifers in almost all of the gas reservoirs, but the formation aquifer sizes varied in gas reservoirs. To investigate the influence of different aquifer sizes on the exploitation performance of fractured gas reservoirs, core 2 was used to investigate the water invasion mechanism at a gas production rate of 1000 mL/min and an initial saturation pressure of 30 MPa. The experimental results were shown in Figs. 5 and 6. From the result of Fig. 5a, when the gas reservoir did not contain formation aquifer, the bottom pressure had an approximately linear relationship with the recovery factor. The producing pressure drop did not vary much with the recovery factor shown in Fig. 5b, and the reason is that the gas was subject to a smaller filtrational resistance during recovery due to the high flow conductivity of fractured gas reservoirs. Thus, the recovery factor of the gas reservoir without aquifer reached as high as 91.2% while the producing pressure drop was only 0.319 MPa at the end of reservoir exploitation.

The relationship between bottom pressure and recovery factor showed a convex shape when different aquifers existed in gas reservoirs. The invasion of formation aquifer provided the energy for gas reservoir exploitation in the initial stage, and the larger the aquifer, the more significant the energy supplement. Thus, a larger aquifer implied a higher bottom pressure when the recovery factor was the same. With more water invading the gas reservoir in the later exploitation stage, however, gas was partly trapped by water, and the reservoir turned from single-phase flow to two-phase flow, which resulted in an increasing filtration resistance and rapid bottom pressure decline. In addition, the larger the aquifer,

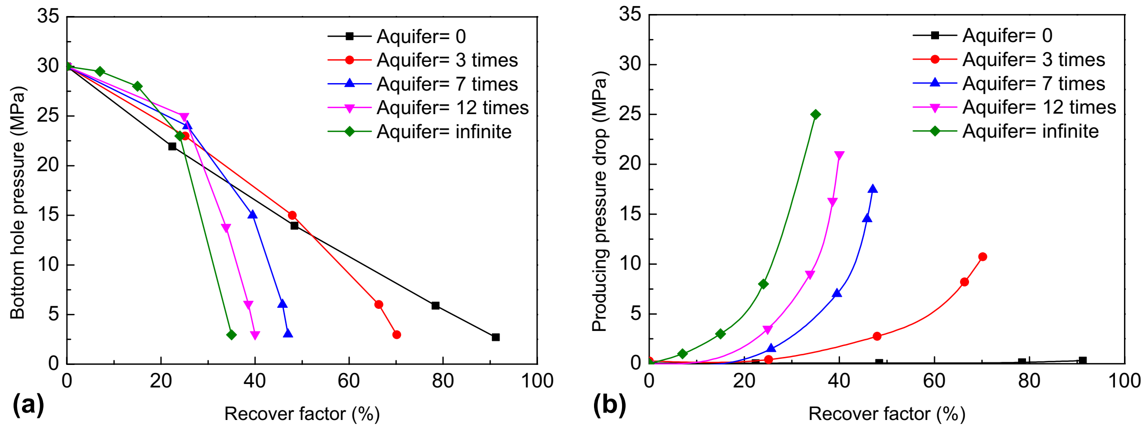


Fig. 5 Bottom hole pressure and producing pressure drop versus recovery factor. **a** Bottom pressure; **b** producing pressure drop

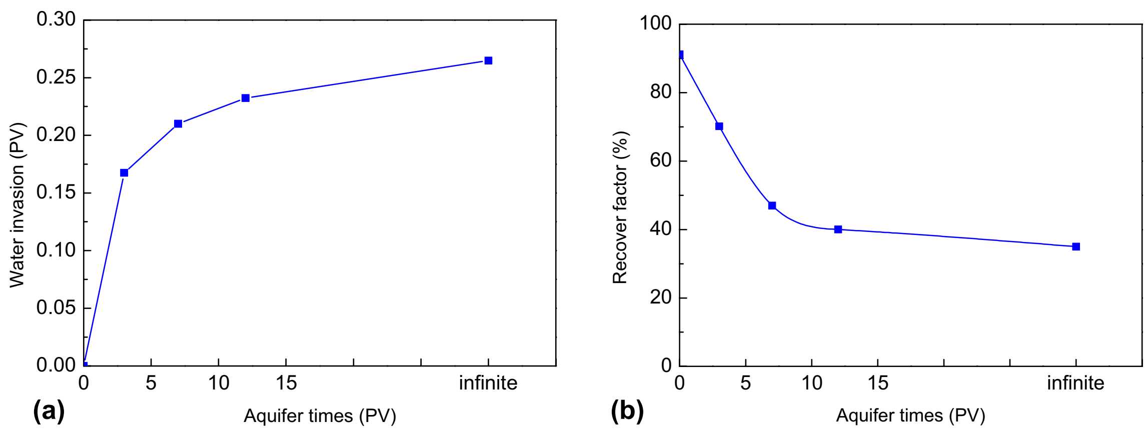


Fig. 6 Water influx and recovery factor versus aquifer times. **a** Water influx; **b** recovery factor

the more rapidly the bottom pressure dropped and the more sharply the producing pressure drop increased. The changes in the water invasion and recovery factor with the aquifer sizes were shown in Fig. 6. The water influx increased gradually as the aquifer increased, but this increase slowed when the aquifer reached a certain value. The recovery factor decreased from 91.2% to 35% as the aquifer increased from 3 times to infinity, which indicated that a draining operation should be conducted when there existed rapid water coning in the case of a shutdown.

Different gas production rates

The gas production rate is an important parameter in the gas reservoir exploitation which determines the productive life and ultimate recovery factor of gas reservoirs. To determine the influence of different gas production rates on the water invasion mechanism in fractured gas reservoirs, core 2 was used to investigate the water invasion mechanism at a formation aquifer of 7 times and an initial saturation pressure of 30 MPa. The changes in the bottom pressure and the producing pressure drop with the recovery factor were shown in Fig. 7. The gas production rate did not strongly affect the bottom pressure or the producing pressure drop when the recovery rate was less than 20%. The bottom pressure and the producing pressure drop varied significantly at different gas production rates in the middle and late stages. The changes in water influx and the recovery factor with the gas production rate were illustrated in Fig. 8a. According to the result, the higher the gas production rate, the lower the water influx. This was because fractures were the primary filtration channels of water invasion in the gas reservoir. Filtration occurred in the matrix that contacted the water in the fractures through the action of water capillary force and wettability. Thus, the water in the fractures gradually invaded the matrix. When the experiment was over, all the fractures were filled with formation water. The higher the gas production rate, the lower the amount of water that invaded the

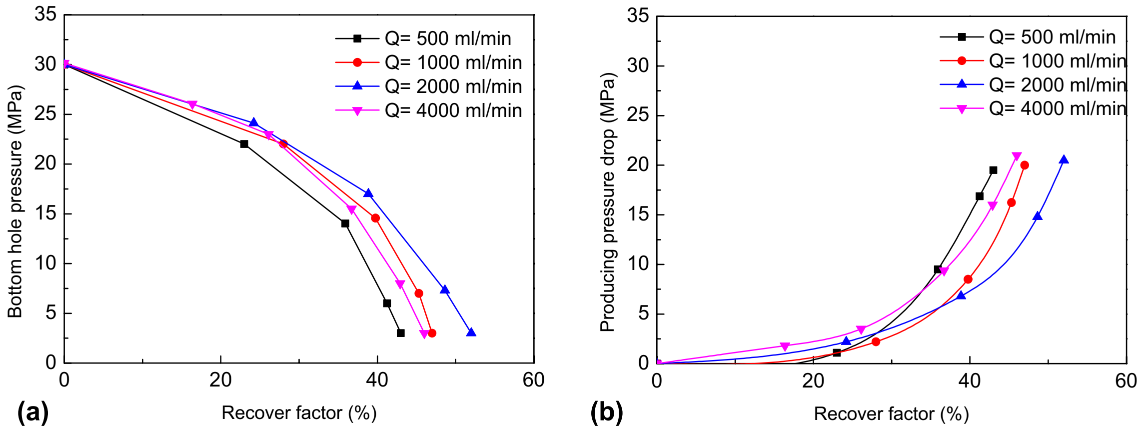


Fig. 7 Bottom hole pressure and producing pressure drop versus recovery factor. **a** Bottom hole pressure; **b** producing pressure drop

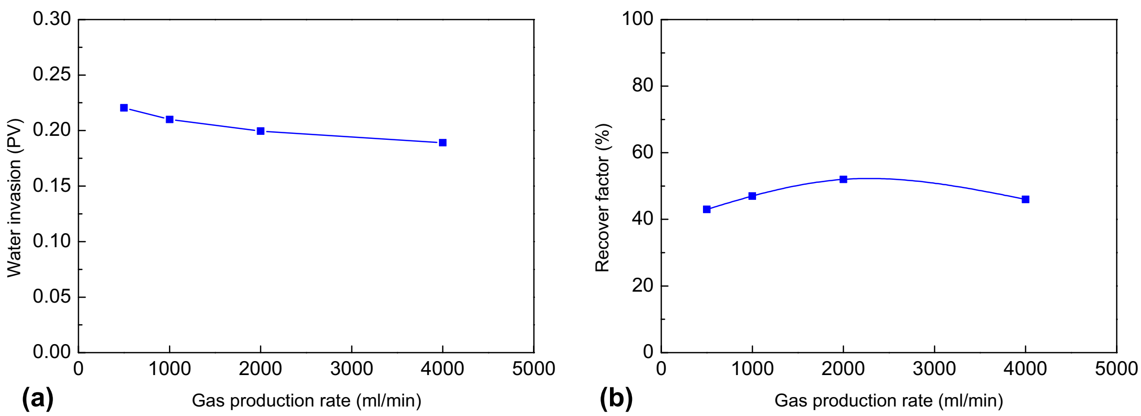


Fig. 8 Water influx and recovery factor versus gas production rate. **a** Water invasion; **b** recovery factor

matrix by means of filtration and the shorter the productive life of the well. In other words, the higher the gas production rate, the lower the water influx. As the gas production rate increased, there was an inflection point of the recovery factor variation in the fractured gas reservoir. It increased and then declined in the production, which was shown in Fig. 8b. When the gas production rate was equivalent to the rate at which the matrix supplied gas to the fractures, the rate was considered optimal since the recovery factor was maximized. Consequently, both the overall reservoir permeability and matrix permeability should be paid attention to the development of fractured gas reservoir to determine an appropriate gas production rate.

Different matrix permeabilities

As the above studies, we knew the matrix permeability of fractured gas reservoirs exerted a significant influence on the reservoir exploitation. Cores 3, 5, and 7 with an overall permeability of 10 mD were selected, in which cores 3 and 5 were fractured cores with a matrix permeability of 0.1 mD and 0.001 mD, respectively, whereas core 7 was a non-fractured core. To investigate the influence of water invasion on gas reservoir exploitation performance when the overall permeability remained the same while the matrix permeability varied, and an experiment on the water invasion mechanism was carried out at an initial saturation pressure of 30 MPa, a gas production rate of 1000 mL/min and a aquifer of 7 times, and the results were illustrated in Figs. 9 and 10.

For non-fractured gas reservoirs with the same overall permeability and the same gas production rate, the producing pressure drop was the lowest when the bottom pressure reached the highest value. This occurred because the large pore throats in the cores were the major reservoir spaces and filtration channels of the gas reservoir without fractures, and the front of the water invasion advanced uniformly. A non-marked water-trapped area was observed in the gas reservoir at the end of the experiment, so the reservoir had a large water influx and a high overall recovery factor. In the presence of fractures, the recovery factor of the gas reservoir

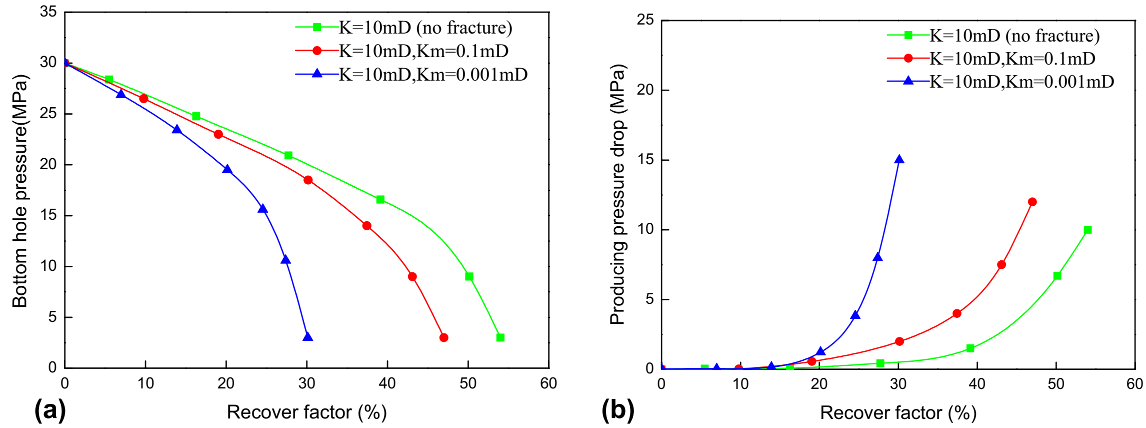


Fig. 9 Bottom hole pressure and producing pressure drop versus recovery factor. **a** Bottom hole pressure; **b** producing pressure drop

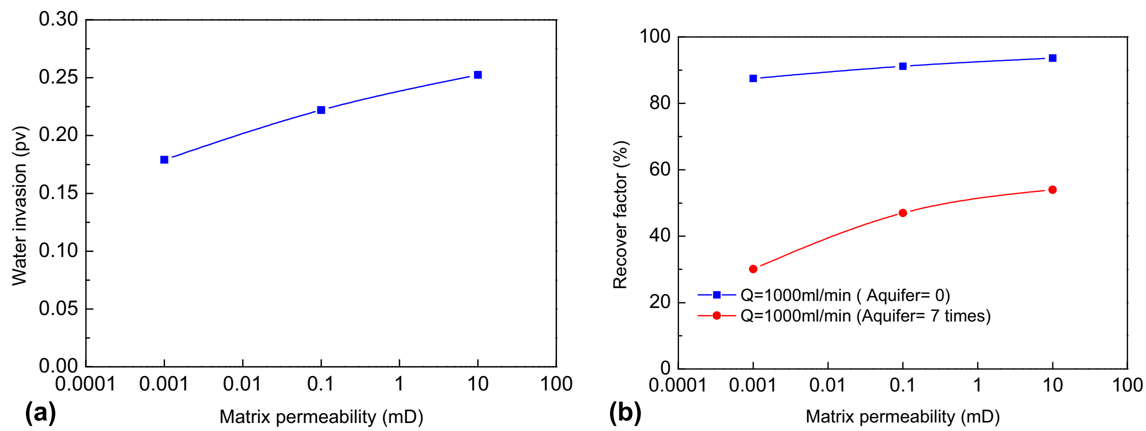


Fig. 10 Water invasion and recovery factor versus different matrix permeability. **a** Water invasion; **b** recovery factor

was only 30%, and the water influx was 0.179 PV when the matrix permeability was 0.001 mD. When the matrix permeability was 0.1 mD, the recovery factor and the water influx were 47% and 0.21 PV, respectively. This is because the lower the matrix permeability, the weaker its capacity to supply gas to fractures and the lower the recovery factor when the gas production rate remained unchanged. Therefore, it implies that we should apply a lower gas production rate in gas reservoirs with low matrix permeability to enhance the recovery factor. On the other hand, the lower the matrix permeability, the higher the fracture permeability and the more easily water flew along the fractures and reached the well bottom. A small water influx would result in rapid water coning of the gas reservoir.

Different fracture apertures

Due to the significant influence of the matrix permeability of fractured gas reservoirs on the exploitation performance, cores with original permeability values of 0.001 mD, 0.1 mD, and 10 mD were selected to create fractures when investigating the influence of fracture aperture on the water invasion mechanism. An experiment with a gas production rate of 1000 mL/min and a aquifer of 7 times was conducted to reveal the influence of fracture aperture on the water invasion mechanism under the conditions of tight, low and high matrix permeability.

As shown in Fig. 11, the pore throats of the cores were poorly developed with a low filtration capability when the matrix permeability was 0.001 mD. The recovery factor of the dry gas reservoir was only 51.22%, and the recovery factor of the gas reservoir with higher bottom water can reach 58% because water provided positive energy to gas reservoir. The invasion of a small amount of water encroached upon the reservoir space of gas and displaced some of it, which enhanced the recovery factor of the gas reservoir. When the micro-fractures were created and core permeability increased to 0.1 mD, the discharge area and filtration capability of the

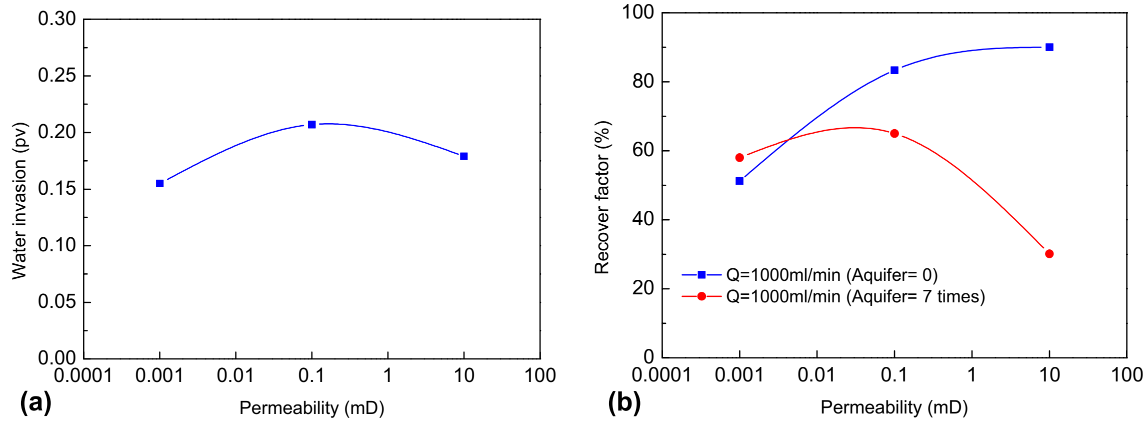


Fig. 11 Water invasion and recovery factor versus matrix permeability of 0.001 mD. **a** Water invasion; **b** recovery factor

cores increased due to the presence of micro-fractures. The recovery factor increased to 83.36% in the dry gas reservoir and to 65% in the reservoir with bottom water. Both values were higher than those obtained when the matrix permeability was 0.001 mD. As the fractures continued to grow and core permeability reached 10 mD, the fractures became the primary means of filtration, along which water flowed forward rapidly to the well bottom. With a small amount of water influx, the gas reservoir would be shut down due to water coning. The recovery factor of the gas reservoir with bottom water was as low as 30%. According to the analysis above, both the recovery factor and water influx of the gas reservoir with bottom water declined after the increase in the fracture scale when the matrix permeability was 0.001 mD, which also indicated that the fracturing scale should be focused on during the exploitation of low-permeability tight gas reservoirs. Therefore, it is necessary to prevent the gas reservoir from being prematurely logged by water that flows forward rapidly along large fractures whilst improving the filtration capability of the gas reservoir using the high flow conductivity of the fractures.

As shown in Fig. 12, the cores with a matrix permeability of 0.1 mD showed better developed pore throats and filtration capability compared with those with a matrix permeability of 0.001 mD. The recovery factor of the dry gas reservoir reached 80.5%, which was far higher than that of the cores with a matrix permeability of 0.001 mD. With the fracture scale growing larger, the core permeability increased from 0.1 mD to 158 mD, during which the recovery factor and water influx of the gas reservoir with decreased bottom water. This was because the increase of fracture not only enhanced the filtration capability of the gas reservoir but also provided advantageous filtration channels for the rapid advancement of water. The recovery factor of the gas reservoir with bottom water will gradually decline when the positive effect of higher filtration capability brought about by the fractures is weaker than what caused by rapid gas entrapment effect of water flowing through the fractures.

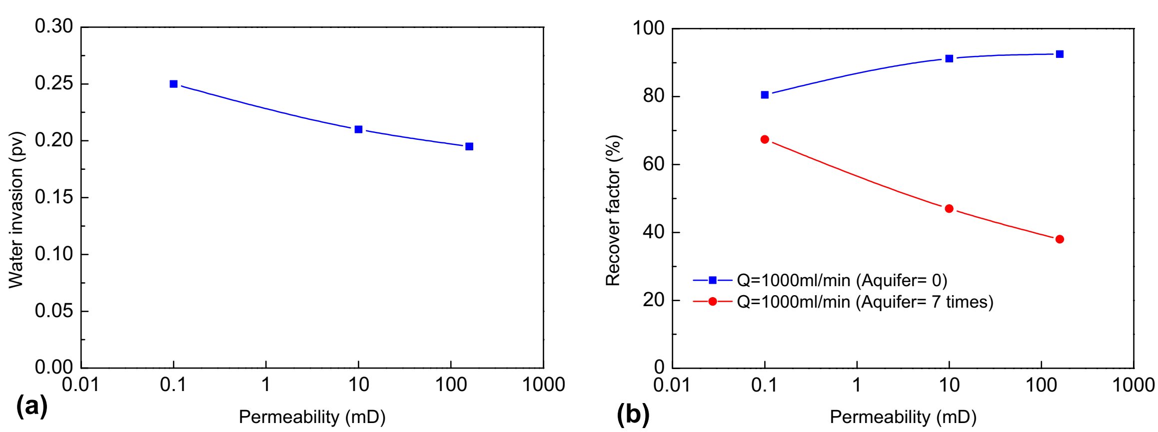


Fig. 12 Water invasion and recovery factor versus matrix permeability between 0.1 mD and 100 mD. **a** Water invasion; **b** recovery factor

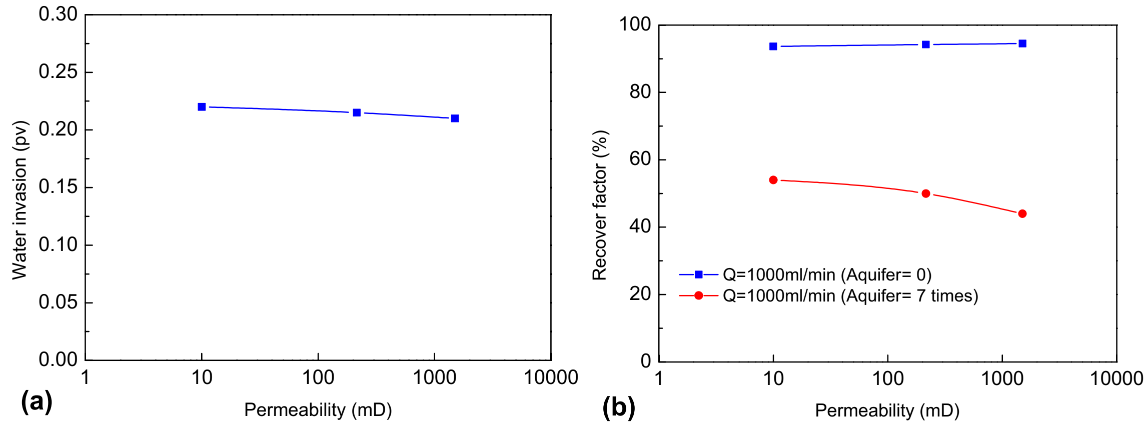


Fig. 13 Water invasion and recovery factor versus matrix permeability between 10 mD and 1000 mD. **a** Water invasion; **b** recovery factor

As shown in Fig. 13, cores with a matrix permeability of 10 mD showed well-developed pore throats and excellent filtration capability. As the fractures grew larger, the core permeability increased from 10 mD to 1500 mD, but the recovery factor and water influx did not vary much. This was because of the core matrix had excellent filtration capability, which resulted in a weakened influence of fracture development on gas reservoir exploitation. It is better to consider the size of the formation water and the gas production rate when exploiting gas reservoirs with a high matrix permeability. Due to the high matrix permeability, the recovery factor of the gas reservoir could be enhanced by means of forced drainage at the time of water invasion.

Conclusion

In this study, the matrix cores with different permeabilities were selected based on the fracture characteristics of the Longwangmiao gas reservoir, and the core samples with artificial fracturing were designed. The experimental simulation of water invasion in fractured gas reservoirs were conducted to understand the flow mechanism, and then the effects such as different bottom water volume ratios, gas production rates, matrix permeability, and fracture apertures on gas production were studied. The following conclusions can be drawn: (1) The larger the aquifer, the more serious the water invasion and the lower the recovery factor, although water does not strongly affect the recovery factor when the water volume ratio exceeds a critical value. (2) The higher the gas production rate, the faster the water invasion and the lower the water influx. The recovery factor reached a peak when the gas production rate was equivalent to the gas supply capacity of the matrix to the fractures. (3) For gas reservoir with the same overall permeability, the higher the matrix permeability, the higher the recovery factor. (4) An appropriate fracturing scale enhanced the recovery factor of the gas reservoir when its matrix permeability was low, but an excessive fracturing scale will make water flow faster along fractures, which further causes a sharp decline in the recovery factor. (5) As the matrix permeability increases, the fractures exert a decreasing influence on the gas reservoir.

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