CSCanada
Advances in Petroleum Exploration and Development
Vol. 8, No. 2, 2014, pp. 6-12
DOI:10.3968/5958

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
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A Simulation Experimental Study on the Gas-Water Saturation Characteristics in the Process of Constant-Speed Gas Production Based on the Microscopic Model

TANG Xiaoyan[a],*

[a] College of Geology and Environment, Xi'an University of Science and Technology, Xi'an, China.
* Corresponding author.

Supported by the scientific research of key laboratory in Shaanxi Province Department of Education (14JS082).

Received 5 October 2014; accepted 2 December 2014
Published online 29 December 2014

Abstract

This paper presents the important findings of research work that was undertaken on the residual water saturation of gas reservoirs that arises from the decrease in pore pressure during a constant-speed gas production process. To study the changes and distribution regularities of water-gas saturation, we used a micro-glass model to conduct a simulation study of the process of constant-speed gas production under pore pressures of 0.5 MPa, 1 MPa and 5 MPa. The results indicate that the total displacement power of the gas reservoir directly affects the development effect. The higher the pore pressures of the gas reservoir whose part of bound water may flow, the more difficult is the development of the reservoir due to the presence of more movable water, resulting in a poorer development effect. For a lower pore pressure of a gas reservoir, the bound water of the gas reservoir is generally immobile, that is, the gas production is single-phase gas seepage, resulting in an improved development effect. Implementing a reasonable development plan for a water-bearing gas reservoir with low permeability is clearly of great significance to ensure its effective development.

Key words: Microscopic model; Constant speed; Gas production; Gas-water saturation; Variation characteristics; Simulation experiment

Tang, X. Y. (2014). A simulation experimental study on the gas-water saturation characteristics in the process of constant-speed gas production based on the microscopic model. *Advances in Petroleum Exploration and Development*, *8*(2), 6-12. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/5958
DOI: http://dx.doi.org/10.3968/5958

INTRODUCTION

To understand the characteristics of gas reservoir development and to formulate a rational and effective development plan, further investigations are required to determine the variation characteristics of gas-water saturation and the microscopic seepage mechanism of a gas reservoir in the process of constant-speed gas production. Most studies of microscopic seepage mechanisms have focused on oil reservoirs, such as the study conducted by J. E. Peden et al., whereas other scholars studied the microscopic seepage mechanism of various production methods[1-3]. Some scholars have already studied the microscopic seepage mechanism of gas-water transportation in a gas reservoir. Amiell et al. studied the distribution of gas-water in a non-steady state using small-scale models[4]. Billiotte et al. studied the distribution characteristics of gas-water for underground gas storage through experiments and numerical simulations[5]. Zhu et al. analyzed the distribution regularities of water saturation for a low-permeability gas reservoir[6]. Li et al. studied the geological modeling and fluid flow simulation of acidic gas processing in the western Wyoming region[7]. Waseda et al. performed an evaluation of the gas seepage characteristics in the process of gas production[8]. Shahverdi et al. proposed an improved model of three-phase relative permeability and hysteresis that could alternately inject gas and water[9]. Gong et al. conducted simulation experiments of hydrated sediments in the process of gas production[10]. Simulation technology for microscopic visualization may further reveal the microscopic seepage characteristics of reservoir fluid and the microscopic distribution characteristics of residual fluid[11].

A simulation experiment based on the micro-glass model is a very convenient and effective method to simulate the seepage mechanism and the distribution regularities of pore fluid under formation conditions. Because of the visual characteristics of this model, researchers can observe and simulate the fluid flow regularity in a pore medium intuitively and clearly. Thus, this paper designed a microscopic visualization experimental system for the analysis of the volcanic gas reservoir in the Junggar basin of China and used the developed system to perform microscopic simulation studies of the gas-water saturation change characteristics during constant-speed gas production.

1. MICROSCOPIC EXPERIMENT MODELS AND PROCESSES

1.1 Development of the Microscopic Model

The microscopic simulation model, which is one of the transparent two-dimensional glass models that uses the photochemical etching process, was independently developed in China. The real pore system of the core casting slice was extracted to the pore network system, which met the requirements of the experiment, and was then precisely photoetched to a plane glass and manufactured through high-temperature sintering. The flowing grid combination of the microscopic model has characteristics that are similar to the shape distribution of the reservoir rock pore system. In this study, the size of the standard model is 40 mm × 40 mm, the pore volume is commonly 50 μL, the minimum pore radius reaches 10 μm, and the section of the pore channel is oval. The wettability on the surface of the model's pore throat is strongly hydrophilic after high-temperature burning. Depending on the experimental requirements, the surface of the model's pore throat can also be treated as neutral.

1.2 Experimental Process of the Microscopic Model

The completed microscopic model was connected to a holder of high temperature and pressure, which enables simulation experiments at normal or high temperatures and pressures according to the requirements of the experiments. The microscopic model was placed horizontally to eliminate the influence of gravity during the experiment. The water used in the experiment was a KCl solution with a concentration of 7,000 mg/L, which was dyed red by eosin such that it is differentiated from colorless nitrogen and thus easy to observe. A certain size of the confining pressure had to be loaded into the model in the high-pressure experiment. During the experiment, the microscopic model was placed under a microscope, the observation hole of which was linked to cameras; the microscope was connected to a digital camera and monitor to observe the experimental process of gas-water seepage at any time. The entire experimental process can be monitored dynamically on a computer and can be saved at any time.

2. VARIATION CHARACTERISTICS AND THE DISTRIBUTION REGULARITIES OF GAS-WATER SATURATION IN THE PROCESS OF CONSTANT-SPEED GAS PRODUCTION

We first assumed that the bound water saturation of gas in a low-permeability gas reservoir cannot change during the process of gas production, that is, the bound water saturation is a constant value. We can observe the seepage regularity of gas-water through a microscope under certain bound water saturation and different pore pressures by micro-simulations. Based on the results, we can discuss the change characteristics of gas-water saturation during the process of constant-speed gas production.

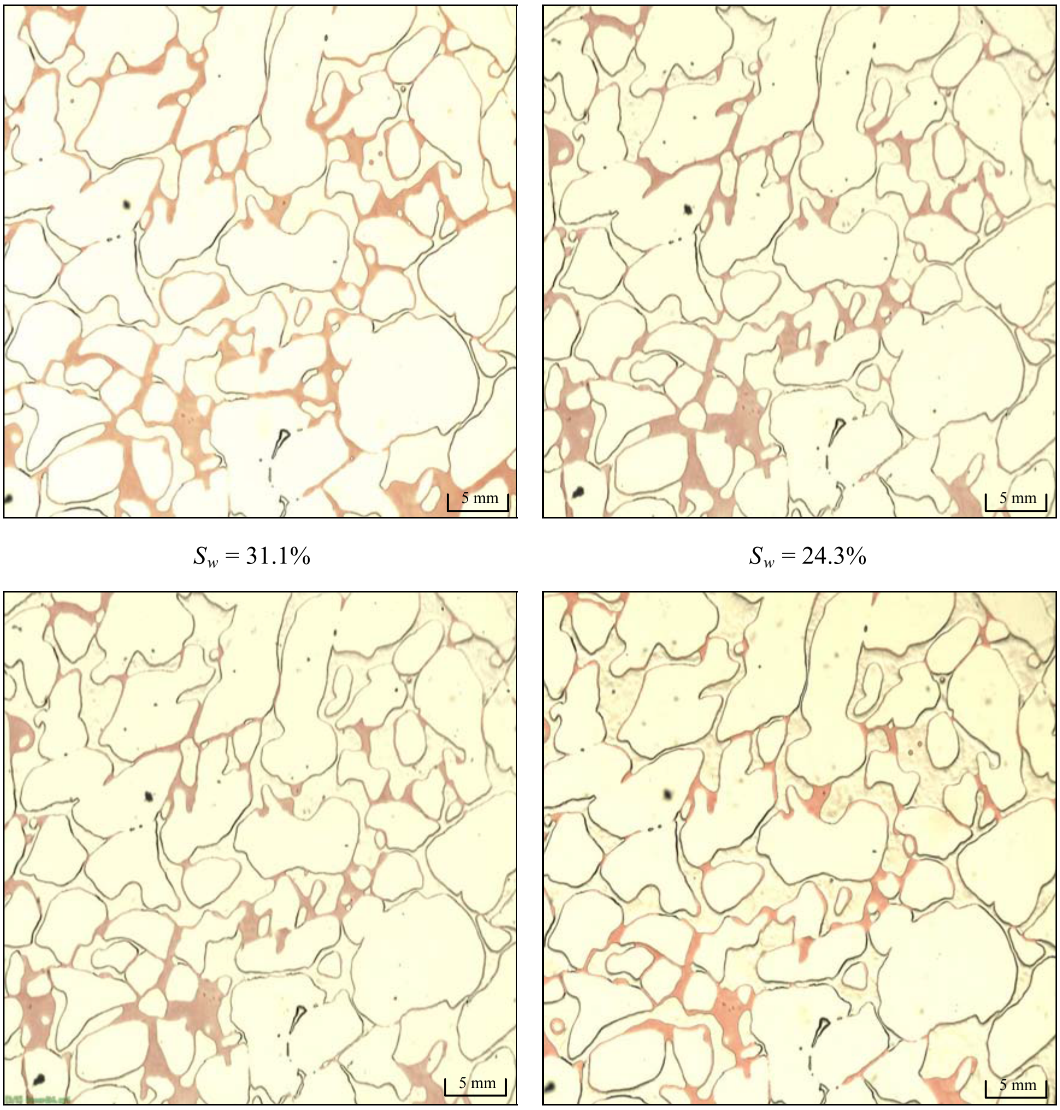
2.1 Simulating the Gas-Water Variation Characteristics and the Distribution Regularities in the Process of Constant-Speed Gas Production Under a Pore Pressure of 0.5 MPa

First, the microscopic model of bound water with a water saturation of 31.1% was established using a gas drive method under a pore pressure 0.5 MPa. Under these conditions, the model began to produce gas by controlling the appropriate gas production rate. The pressure drop during the gas production process was recorded, and the gas and water saturation of the corresponding pore pressure in this model was calculated.

Figure 1 shows that the flow characteristics of residual water in the model are obvious and that the water saturation slightly decreases when the pore pressure begins to decrease. When the pressure drops to 0.35 MPa, the water saturation fell to 24.3% in the model; it was difficult to observe the obvious characteristics of water flow in the model. The water was mainly extracted along the pore wall by gas. In some cases, we observed the phenomenon in which the water of the pore wall coalesced. Finally, the water saturation in the model was reduced to 12.1%. The small water droplets in the macropore path as well as the gas in the pore throat basically do not flow during the gas production process. Most of the final bound water remains stranded in the small throat and in the blind end of the pore throat.

2.2 Simulating the Gas-Water Variation Characteristics and the Distribution Regularities in the Process of Constant-Speed Gas Production Under a Pore Pressure of 1 MPa

First, the microscopic model of bound water with a water saturation of 34.6% was established using a gas drive method under a pore pressure of 1 MPa. Under these conditions, the model began to produce gas by controlling the appropriate gas production rate. The pressure drop during the gas production process was recorded, and the gas and water saturation of the corresponding pore pressure in this model was calculated.

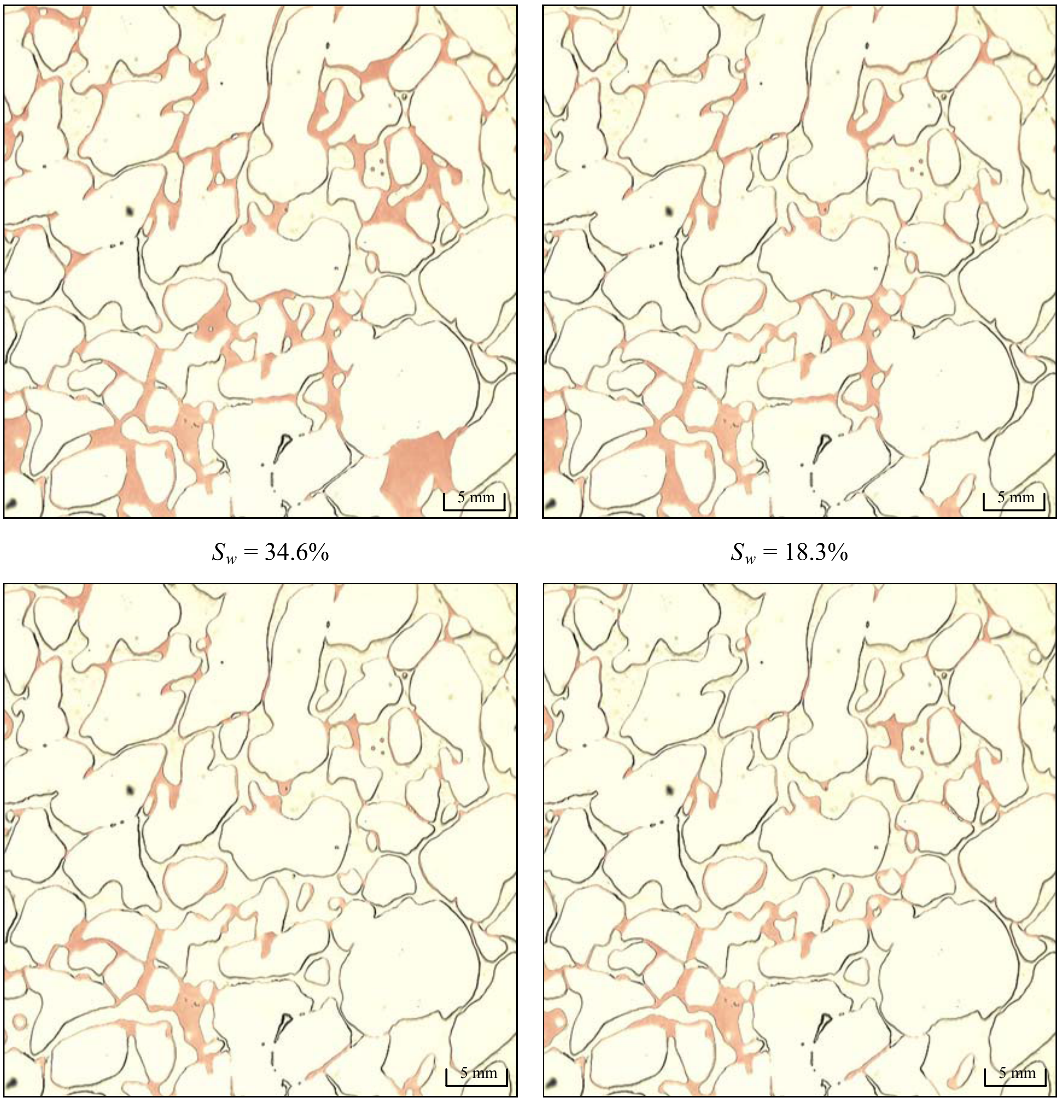


S_w = 31.1% S_w = 24.3%

S_w = 18.4% S_w = 12.1%

Figure 1
Distribution Characteristics of Gas-Water Saturation in the Process of Constant-Speed Gas Production Under a Pore Pressure of 0.5 MPa

When the pore pressure begins to reduce, the flow phenomenon of the residual water in the model is not obvious, and the water saturation decreases (see Figure 2). When the pressure decreases to 0.88 MPa, the water saturation in the model decreased to 18.3%. It was difficult to observe any obvious characteristics of the water flow in the model. The water was mainly extracted along the pore wall by gas. When the drive energy reached a certain value, some of the water on the pore wall was observed to coalesce. As the pore pressure is decreased, the coalesced water is removed by the gas. As the process is constantly repeated, the water saturation in the pore continues to decrease. As the velocity of the gas flow is increased, the water of the pore walls is converted into aerosol and removed by the rapid flow of gas. Finally, the water saturation in the model is reduced to 10.9%. This result indicates that the decrease in the final residual water saturation arises from an increase in the pore pressure. Most of the final bound water remains stranded in the small throat, attached to the pore wall and in the blind end of the pore throat.



S_w = 34.6% S_w = 18.3%

S_w = 14.3% S_w = 10.9%

Figure 2
Distribution Characteristics of Gas-Water Saturation in the Process of Constant-Speed Gas Production Under a Pore Pressure of 1 MPa

2.3 Simulating the Gas-Water Variation Characteristics and the Distribution Regularities in the Process of Constant-Speed Gas Production Under a Pore Pressure of 5 MPa

The microscopic model of bound water with a water saturation of 34% was established using the gas drive method under a pore pressure of 5 MPa. Under these conditions, the model began gas production by controlling the appropriate gas production rate. The pressure decrease during the gas production process was recorded, and the gas and water saturation of the corresponding pore pressure was calculated using this model.

Based on the experimental process of gas production shown in Figure 3, we found that the pore pressure began to decline and that the water saturation in the model diminishes to some extent. However, the phenomenon of water flow was not clearly observed. When the pressure decreased to 4.6 MPa, the water saturation in the model fell to 28.7%. With the continuous production of gas, the pore pressure gradually decreases, and the corresponding water saturation continually declined. In the end, when the final pore pressure decreased to 1 MPa, the corresponding water saturation was only 6.9%. The results indicate that higher pore pressures result in lower residual water saturation during the process of gas production. The resulting bound water in the model primarily remains stranded in the small throat, adhered to the pore walls, and at the blind end of the pore throat. With an increase in the pore pressure, the water attached to the pore wall decreases significantly.

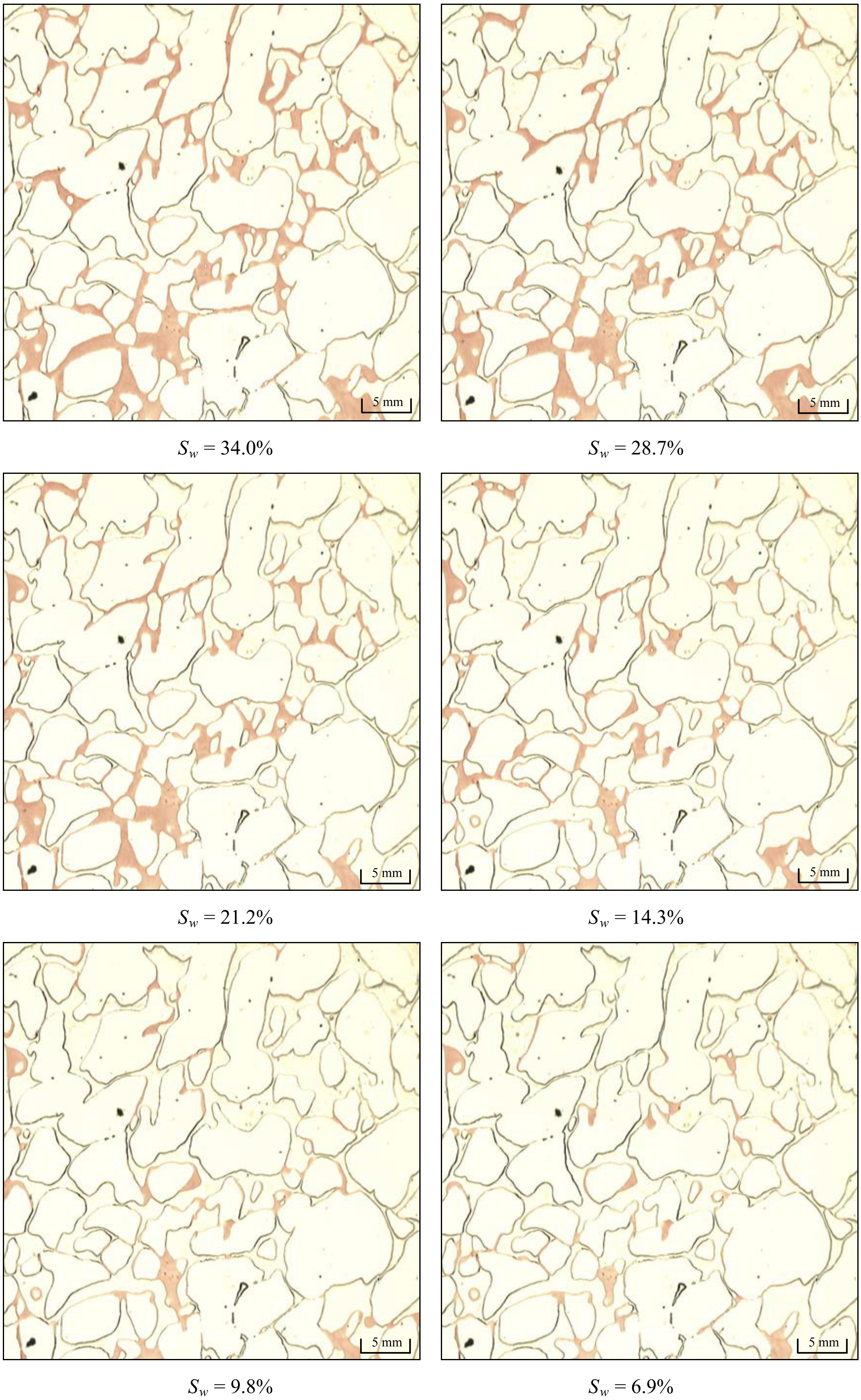


Figure 3
Distribution Characteristics of Gas-Water Saturation in the Process of Constant-Speed Gas Production Under a Pore Pressure of 5 MPa

3. MICROSCOPIC MECHANISM AND SEEPAGE CHARACTERISTICS OF GAS-WATER IN THE PROCESS OF GAS PRODUCTION

During the early to middle phases of gas production, the gas mainly seeps into the middle of the large pore throat, and the water is found in the small pore throat and the walls of the large pore throat. During the late stage of gas production, with a decrease in the gas reservoir pore pressure, the flow rate of the gas is reduced. The remaining water is mainly distributed in the throat, the blind end and the small throat pore. The residual gas, in the form of an irregular column and small water droplets, mainly remains in the middle of the pore and the pore group surrounded by a small throat; the gas-water interlock phenomenon is obvious (see Figure 4), and the seepage resistance of gas greatly increases such that the effect of gas reservoir development is reduced.

Figure 4
Microscopic Mechanism of the Seepage and the Distribution of Gas-Water During the Gas Production Process

Due to gas flow during the process of gas production, the residual water is mainly removed by the gas along the pore wall. When the drive energy reaches a certain value, the water on the pore wall will coalesce. With a decrease in the pore pressure, the coalesced water is removed by the gas. As this process is constantly repeated, the water saturation of the pore constantly decreases; when the flow velocity of gas is larger, the water attached to the pore wall is converted into aerosol and removed by the rapid flow of gas, as observed in the simulations.

In the gas-swept area, the residual water is mainly distributed in the small throat, the blind end, the large pore surrounded by a small throat, and the side wall. Due to the wetting action of water, the capillary pressure in the pore throat and the sharp corners is the strongest, and it is difficult to remove these water droplets via the gas flow. Even if the water in the small throat and sharp corners is removed for the moment, the water can be inhaled into these small throat and sharp corners because of the strong imbibition effect of the capillary.

Because the pore throat of the underground reservoir has strong heterogeneity, the gas-water distribution in the pore structure during the process of gas production is complicated. Due to the high-speed cutting action of the pore structure, the local area of the reservoir appears to show the interlocking of gas and water. Because the rock types of the water flow of the gas reservoir exhibit hydrophilicity, the wall of the pore throat forms a water membrane that gradually thickens with an increase in the running cycles. The filtration ability of the gas phase decreases, and the filtration ability of the water phase increases accordingly.

For a gas reservoir, the water phase is commonly in the wetting phase and is mainly distributed in the fine pore throat and pore wall surface. The gas is found within the pore, and the micro-pore throat surrounds and controls the pore-body; thus, each sealing state of gas-water is formed. The output of the gas phase must break the bondage of water in the pore throat region during gas development. During the process of gas reservoir development, as the reservoir pressure declines gradually, the pressure drop is transmitted to the intrapore gas, which causes the gas volume to rapidly expand and thereby extrude the water from the pore surface and produce the impetus for the water phase of the micro pores. As long as the impetus is greater than the binding capillary force of the micropore throat, the residual water that is in the micropore throat can be driven out, which causes it to migrate and become mobile water. Due to the low permeability of a volcanic gas reservoir due to the development of a micropore throat, the residual water saturation is higher; as a result, the pressure gradient is large during the process of depletion development. Thus, the output of moving water is larger, which has a strong impact on the gas reservoir capacity.

CONCLUSION

The experimental results show that, for gas reservoirs with the same gas saturation, a higher pore pressure is associated with a greater gas flow velocity during the process of gas production and with a lower residual water saturation, as observed in the model. The lower the pore pressure is, the smaller the gas seepage velocity is during the process of gas production, and the higher the final residual water saturation is in this model. These results indicate that the size of the displacement power directly affects the mobility of bound water in the process of gas production, that the bound water of the gas reservoir is generally immobile under a low displacement pressure, that the gas production process is single-phase gas seepage (so the development is difficult to reduce), and that the development effect is improved. However, part of the bound water is likely to flow under the high displacement pressure, and a higher pressure results in a greater amount of moving water. Consequently, the development difficulty of a gas reservoir is greater, and the ultimate development effect is worse.

Due to the water in the pore wall and the fine throat, both the relative permeability of the gas phase and the seepage ability are significantly reduced. The water is extensively distributed along the tiny throat, and effective traps form for the gas in the large pore, that is, the pore water lock is serious. Coupled with the low permeability of the gas reservoir, these conditions ultimately lead to an increase in the development difficulty for a low-permeability water-bearing gas reservoir, and the production degree is low.

Note that the microscopic model experiment has some limitations: The model itself is made of glass and exhibits a large difference from the formation property, and the model exhibits restrictions for the throat radius during the process of model development. The model of the throat radius is generally more than 10 microns, and it is very difficult to make a smaller throat radius; as a result, the microscopic seepage conditions of a low-permeability reservoir cannot be simulated because most throat radius values are less than 10 microns. Thus, the simulation results of the microscopic visual model are mainly used in laboratory research and some theoretical explanations, especially for a low-permeability reservoir, and there is a large difference in the pore throat size of the simulations.

ACKNOWLEDGMENTS

The authors would like to acknowledge reviewers and the editor for their many helpful comments and suggestions that improved the manuscript significantly.

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