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Study on water invasion law and development strategy of fractured gas reservoir based on pore throat structure

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ABSTRACT

In this paper, a systematic technology is developed to study the influence of pore-throat structure and fracture development on the water invasion behavior of fractured gas reservoirs, quantitatively characterize the law of water invasion, and then formulate a reasonable working system. In the experiment, nuclear magnetic resonance (NMR) and high-pressure mercury injection (HPMI) were used to characterize the pore structure of the core samples, and the distribution of the invaded water phase in the pore throat was clarified. The effect of water phase distribution on gas phase permeability was obtained by displacement test. Based on the existing capillary bundle model, three types of gas-water microscopic occurrence and seepage modes are divided from the microscopic pore-throat structure. Furthermore, considering the high conductivity of fractures in the reservoir, a mathematical model was formulated and generalized to characterize the seepage characteristics of fractured gas reservoirs. In this way, the effects of pore-throat structure and fracture development degree on water invasion law are comprehensively examined and analyzed. Subsequently, the model was promoted and applied to the dynamic prediction and scheme formulation of a fractured gas reservoirs. The research shows that during the flow of edge-aquifer along the fracture, it will invade the matrix under the action of large capillary force and reserve in a large number of small pore throats, thus forming a large amount of closed residual gas. which greatly restricts the gas recovery rate and recovery rate of the reservoirs. The simulation shows that the production pressure difference in the study area should be controlled within 5 MPa, and the early strong drainage measures at the edge should be used to assist in increasing production. Reasonable water control measures can improve the recovery rate of gas reservoirs by more than 15 %.

Keywords: fractured gas reservoir, pore throat structure, water invasion law, development strategy

NONMENCLATURE

Abbreviations	
NMR	Nuclear magnetic resonance
HPMI	High-pressure mercury injection
Symbols	
r	Capillary radius (m)
Δp	Pressure drop (Pa)
μ	Fluid viscosity (Pa·s)
L	Core length, m
$f_n(r)$	Distribution frequency of the number of capillaries when the capillary radius is r
$f_k(r)$	Permeability distribution frequency when the capillary radius is r
n	Number of capillaries
R	Core radius (m)
k	Core permeability (mD)
R_g	Resistance of the gas phase capillary (pa·s·m^{-3})
J	Jamin effect coefficient of gas flow,
L_C	Length of a single capillary (m)
P_m	Matrix pressure (Pa)
P_f	Fracture pressure (Pa)
l_g	Length of the gas in the capillary (m)
δ	Tortuosity for a capillary

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μ_w	Apparent viscosity of water (pa·s)
μ_g	Apparent viscosity of gas (pa·s)
q_g	Gas production rate ($m^3 \cdot s^{-1}$)
$q_{in,w}$	Water invasion speed ($m^3 \cdot s^{-1}$)
R_{wg}	Resistance of gas-water two-phase in the capillary ($pa \cdot s \cdot m^{-3}$)
S_w	Water saturation
V	Volume of flow unit (m^3)
ϕ	Porosity (%)
v_{gf}	Gas flow velocity in the fracture ($m \cdot s^{-1}$)
v_{wf}	Water flow velocity in the fracture ($m \cdot s^{-1}$)
K_f	Fracture permeability (mD)
k_{rg}	Gas relative permeability
k_{rw}	Water relative permeability
ρ_g	Gas density ($kg \cdot m^{-3}$)
$q_{g,p}$	Gas production of production wells ($m^3 \cdot s^{-1}$)
$q_{w,p}$	Water production of production wells ($m^3 \cdot s^{-1}$)
$q_{f,w,in}$	Amount of edge water invading the reservoir along the fractures ($m^3 \cdot s^{-1}$)
C_m	Rock compression coefficient of the reservoir (Pa^{-1})
K_{fi}	Permeability under the original formation pressure (mD
p_i	Initial formation pressure (Pa)
S_{wi}	Initial water saturation (Pa)

1. INTRODUCTION

In recent years, under the background of energy conservation and emission reduction, the development of unconventional gas reservoirs has achieved rapid development. In low-permeability and tight gas reservoirs, fractures are widely developed in reservoirs [1] and gas reservoirs are generally connected to water bodies, which will lead to the invasion of edge water or bottom water along fractures during gas production, dividing gas reservoirs, and forming a large amount of water-sealed gas in gas reservoirs [2], which greatly restricts the efficient development of gas reservoirs.

There have been a lot of studies on the macroscopic characteristics of physical simulation experiments on the water invasion mechanism of fractured gas reservoirs [3-5]. In the evolution process of low-permeability tight gas reservoirs, the continuous injection of dry gas will greatly improve the water carrying capacity, so that the reservoir generally has ultra-low water saturation [6]. When the edge water invades the formation along the fracture, affected by the capillary force and wettability, the matrix in contact with the water body in the fracture occurs imbibition, resulting in a rapid decrease in gas permeability because water phase will preferentially occur in the small throat. A large amount of gas is sealed in the rock pores and is difficult to be produced. As a result, the recovery degree of fractured gas reservoirs is much lower than that of porous gas reservoirs [7-10]. Therefore, the key to the effective development of fractured gas reservoirs is to clarify the influence of fracture and pore throat characteristics on water invasion, and then formulate a reasonable production system.

Wang J, Hu Yong et al. [5,11] studied the influence of fracture core on reservoir imbibition through physical simulation. Fatemeh Ghasemi et al. [12] established a mathematical model for evaluating spontaneous imbibition of gas reservoirs based on the influence of different factors on gas reservoir seepage. The study found that fractures are the main channel for gas-water flow, fracture development is the root cause of serious water production in the later stage of development. The retained water in pores and throats will reduce the gas permeability, resulting in water lock, and the lower the permeability, the smaller the porosity of the reservoir, the stronger the imbibition of water, the more serious the reservoir damage. At the same time, the occurrence of water invasion will form a gas-water two-phase flow in the fracture, and the resistance of the gas flow increases, which greatly reduces the conductivity of the fracture to the natural gas [2], resulting in the residual gas in the water invasion area is difficult to be produced.

At present, the suppression methods of water invasion mainly include drainage gas recovery, pressure control production [13-15]. Li Xiaoping [16] theoretically deduced the conditions that the gas seepage velocity should meet when maintaining the stable movement of the gas-water interface, and obtained the expression of reasonable production pressure difference and production of gas wells. The research shows that too high or too low gas well production will affect the development effect of gas reservoirs. Optimizing a reasonable production system is very important for controlling water intrusion.

The evaluation methods of water invasion law in fractured gas reservoirs have their own advantages and disadvantages. Through experiments and core analysis, the mechanism of fracture channeling and matrix imbibition can be characterized, but the research scale is small, and the characterization of water invasion law at gas reservoir scale is insufficient. The existing evaluation models are mostly based on the improvement of Darcy law and material balance equation, and the pore throat structure characteristics of rock are not considered enough. It is difficult to effectively describe the water-sealed gas law in the process of water invasion and the characteristics of gas-water two-phase flow in fractures. In this work, the microscopic pore throat structure and gas-water distribution characteristics of the rock in the study area were evaluated by combining the experimental test and theoretical quantification. A set of mathematical characterization models for the seepage characteristics of fractured gas reservoirs was established, and the model was applied in the actual block. The water invasion law of fractured edge water gas reservoirs was clarified and the production system was optimized, which provided a theoretical basis for the efficient development of such gas reservoirs.

2. MATERIAL AND METHODS

2.1 Description of study area

A block is located in the Kelasu tectonic belt of Kuqa Depression, Tarim Basin. The main part is a sudden structure with small dip angle clamped by two hedge faults, the north and south sides are controlled by faults, and the water body is developed on both sides of the east and west, which belongs to a typical layered edge water gas reservoir. The burial depth is more than 6000 m, the original formation pressure is 87 MPa, and the average permeability is 0.47 md. The natural fractures density in the reservoir can reach 0.3-0.6/m and the fractures trend is basically consistent with the fault trend. The edge water is developed at the east and west wings of the gas reservoir. The static water body multiple is 1.31 through the early trial production evaluation, which belongs to the limited water body.

2.2 Experimental

2.2.1 Experimental materials

The typical core of study area with porosity of 8.65 % and permeability of 0.47 md was selected. The washed core was cut into a core plug with a diameter of 2.5 cm and a length of 10.0 cm. In order to eliminate the impurities in the formation water, a synthetic brine with a salinity of 35000 mg / L was prepared, and its viscosity at normal pressure and 60 ℃ was 0.478 mPa • s.

2.2.2 NMR experiment

The 6.0 cm core plug was cut from the core sample for NMR tests. Firstly, the core plugs were vacuumed in a container. Then, the synthetic brine was pressurized and pumped into the container, and the piston pump was used to pressurize the container to 19 MPa to ensure that the T2 spectrum measured for the core plug after water saturation accurately reflects its pore size distribution. Then, for saturated rock samples, the surface water was removed by wetting filter paper, and then the core plug was evaluated by NMR pulsars to record the initial state. Finally, the rock sample was loaded into a centrifuge and centrifuged at 3000r / min, 5000r / min, 6600r / min, and 9350r / min for 30 min. After each centrifugation, NMR test was performed and the corresponding data were recorded.

2.2.3 HPMI tests

A 3.0 cm core plug was cut from the core sample, and the HPMI test was performed with a fully automatic mercury porosimeter with an accuracy of 0.001 MPa. The Washburn equation and the Purcel method [17] can be used to calculate the permeability contribution corresponding to the pore throat radius.

2.2.4 Gas drive water experiment

(1) The rock sample after nuclear magnetic resonance is dried ; (2) The rock sample is saturated with water, and the core weight is measured before and after the saturated water to calculate the water saturation; (3) Put the core into the gripper, with nitrogen constant pressure 1MPa displacement, and record the displacement pressure, gas production and water production data at different times. (4) Repeat the test (1)-(3) for a total of 3 times to eliminate the influence of experimental errors on the data.

2.3 Mathematical model

2.3.1 Model assumption

In fractured gas reservoirs, the pressure difference between the matrix and the fracture is the driving force for the gas phase to flow into the fracture, and because the reservoir generally exhibits strong hydrophilicity [4-8], the water phase will produce self-priming due to the presence of capillary force. Thus, in the reservoir, there will be a two-phase co-infiltration phenomenon in which the water phase invades the matrix from the fracture and the gas phase flows from the matrix into the fracture (see Fig. 1). Also, the flow characteristics of the gas-water two-phase in the fracture and matrix media are very different. In order to explore the influence of fracture and pore throat structure on water invasion law more comprehensively, this paper establishes the seepage model of fracture and matrix respectively. The equivalent model diagram is shown in the Fig. 1, and the following assumptions are made :

(1) There are only gas-water two phases without material exchange in the gas reservoir, and the temperature remains unchanged.

(2) Gas is compressible fluid, which is described by gas state equation, and the compressibility of water and rock is ignored.

(3) The matrix in the reservoir is the space for fluid storage, and the fracture is only used as a flow channel. Gas and water will first flow from the matrix into the fracture, and then flow from the fracture into the wellbore.

(4) The fracture system in the reservoir is divided into transverse fractures parallel to the flow direction and micro-fractures perpendicular to the flow direction. Both of them divide the matrix into different flow grids. The penetrating fractures are the main channels of fluid flow (see Fig. 1).

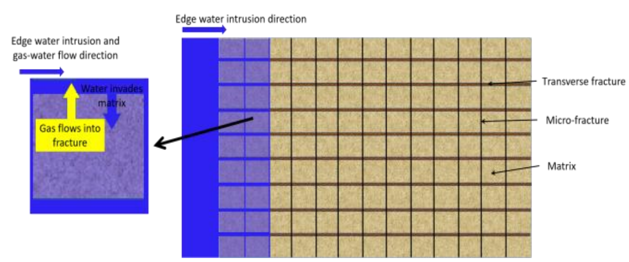

Fig. 1. Equivalent model of fractured gas reservoir

2.3.2 Matrix system model

The pore-throat structure of a rock dictates its seepage behaviour especially in low permeability reservoirs. Based on the capillary bundle model and HPMI experiment, the contribution of capillary with different radii to permeability and porosity can be characterized. As such, On the hypothesis of fact that the fluid flows mainly through the parallel capillary bundles in a core, the characteristics of its pore-throat structures is quantified by combining it with the HPMI data. According to the Poiseuille's law, the volumetric flow rate in a single capillary can be expressed as:

$$q_r = \frac{\pi r^4}{8} \times \frac{\Delta p}{\mu L} \qquad (1)$$

where r is the capillary radius, m; △p is pressure drop, Pa; μ is fluid viscosity, Pa • s; and L is the core length, m.

According to the Darcy's law, the fluid flow of a single capillary in porous media can be expressed as:

$$q_r = \frac{k f_k(r) \times \pi R^2 \times \dfrac{\Delta p}{\mu L}}{n \times f_n(r)} \qquad (2)$$

where $f_n(r)$ indicates the distribution frequency of the number of capillaries when the capillary radius is r; $f_k(r)$ denotes the permeability distribution frequency when the capillary radius is r conditioned to the HPMI test [17]; n is the number of capillaries in the core; R is the core radius, m; and k is the core permeability, mD.

Obviously, for a given porous medium, the relationship between the aforementioned two distribution frequencies is experimentally obtained as:

$$f_n(r) \propto \frac{f_k(r)}{r^4} \qquad (3)$$

In fractured gas reservoirs, the water phase will preferentially accumulate in small throats. Therefore, gas-water distribution and seepage law are obviously greatly affected by the pore throat structure of the matrix. Based on the existing capillary bundle model, combined with the gas-water distribution characteristics obtained from the experiment, three gas-water distribution modes are defined (see Fig. 2), and the corresponding mathematical models are established to describe :

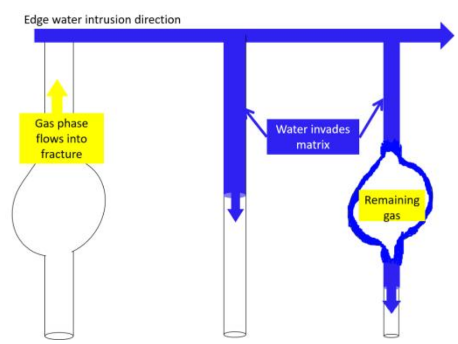

Fig. 2. Gas-water distribution in pore-throat

(1) When the capillary radius is large, the capillary force is small, and the gas in the matrix can overcome the capillary force and enter the fracture. Therefore, the gas production rate at a given time t_i can be expressed as:

$$q_g(t_i) = \int_{rw}^{r\max} \frac{\left[P_m(t_i) - P_f(t_i) - P_{cw}(r)\right]}{R_g(r, t_i)} \times n \times f_n(r) dr \qquad (4)$$

where, R_g is the resistance of the gas phase capillary.

$$R_g(r)=\frac{8J\mu_g\delta L_C}{\pi r^4} \tag{5}$$

where, J is the Jamin effect coefficient of gas flow [20-21], which is related to the water saturation of the core. L_C is the length of a single capillary; P_{in} and P_{out} are the pressure at its inlet and outlet, respectively; l_w is interface position of the displacing water in the capillary; δ is tortuosity for a capillary; μ_w and μ_g are the apparent viscosity of water and gas flowing in the capillary, which is related to the wettability of rock [22].

(2) When the capillary radius is small, the capillary force is large, the gas in the matrix is difficult to overcome the capillary force, and the water phase will enter the matrix from the smaller *throat* under the influence of the capillary force. The water invasion speed can be characterized as :

$$q_{in,w}(t_i)=\int_0^{rw}\frac{\left[P_f(t_i)+P_{cw}(r)-P_m(t_i)\right]}{R_{wg}(r,t_i)}\times n\times f_n(r)dr \tag{6}$$

where, R_{wg} is the viscous resistance of gas-water two-phase in capillary.

$$R_{wg}\left(r,t_i\right)=\frac{8\left\{\mu_w\delta\left[L_C-l_g\left(r,t_i\right)\right]+J\mu_g\delta l_g\left(r,t_i\right)\right\}}{\pi r^4} \tag{7}$$

(3) When the water phase invades the matrix from a smaller capillary, it will pass through a larger pore space. According to the existing microfluidic experiments, due to the hydrophilicity of the rock, the water phase will flow close to the wall and block the throat, thus sealing the gas phase in the pores and forming remaining gas[3]. Therefore, in a single capillary, assuming that the water phase only occupies the capillary and throat, the propulsion speed of the water phase can be characterized as equations 6.

Thus, three kinds of gas-water distribution and seepage modes are divided. Affected by water invasion, the water saturation in the reservoir can be expressed as :

$$S_w(t_i)=\frac{\int_0^{t_i}q_{in,w}(t)}{V\times\phi}+S_{wi} \tag{8}$$

2.3.3 Matrix system model

The fracture is only used as a channel for gas-water flow, and its motion equation is:

$$v_{gf}=-\frac{K_fK_{rg}}{\mu_g}\nabla p_f \tag{9a}$$

$$v_{wf}=-\frac{K_fK_{rw}}{\mu_w}\nabla p_f \tag{9b}$$

where K_f is the fracture permeability, k_{rg} is the gas phase permeability, k_{rw} is the water phase permeability, and ∇p_f is the pressure gradient in the fracture, v_{gf} and v_{wg} represent the flow rate of gas and water respectively.

The continuity equation can be written as :

$$-\nabla\left(\rho_g v_{gf}\right)-q_g=0 \tag{10a}$$

$$-\nabla\left(\rho_w v_{wf}\right)-q_w+q_{\mathrm{f,w,in}}=0 \tag{10b}$$

where q_g and q_w are gas production and water production of gas wells. $q_{f,w,in}$ is the amount of edge water invading the reservoir along the fracture.

2.3.4 Additional equation

(1) Stress sensitivity

The stress sensitivity effect has a weak influence on porosity, but has a strong influence on permeability[23]. For the capillary bundle model, the change of capillary radius with stress is :

$$C_m=\frac{n\pi}{\phi}r\frac{dr}{dp} \tag{11}$$

where C_m is the rock compression coefficient of the reservoir and is porosity.

For fracture:

$$K_f=K_{fi}e^{-\alpha(p_i-p)} \tag{12}$$

where K_{fi} represents the permeability under the original formation pressure; p_i represents the original formation pressure.

(2) Boundary conditions

At the wellbore, the bottom hole flow pressure values at different times obtained by pressure measurement are used as the internal boundary conditions :

$$p(t_i)\big|_{x=0}=p_{wf}\left(t_i\right) \tag{13}$$

In a structural trap, its outer boundary can be regarded as closed, and the boundary condition is :

$$\left.\frac{\partial p}{\partial x}\right|_{x=a}=0 \tag{14}$$

(3) Initial condition

At the initial time, the formation pressure and water saturation are obtained by trial production and logging data.

$$p\left(x\right)\big|_{t=0}=p_i \tag{15}$$

$$S_w\left(x\right)\big|_{t=0}=S_{wi} \tag{16}$$

Because the establishment of the model is based on the matrix-fracture dual medium model, and determing the contribution fraction of porosity and permeability corresponding to different capillaries in a given reservoir using an accurate function is mathematically difficult, it is difficult to obtain the analytical solution directly. The model is solved numerically according to the matrix-fracture sequence iterative solution, provided some parameters (i.e., viscosity, contact angle of oil and water, capillary pressure curve of core) are experimentally determined.

3. RESULTS AND DISCUSSION

3.1 Analysis of pore throat structure in the study area

The distribution characteristics of gas and water in the core can be obtained by NMR test, and the NMR analysis spectrum of the sample in the study area is shown in the Fig. 3.

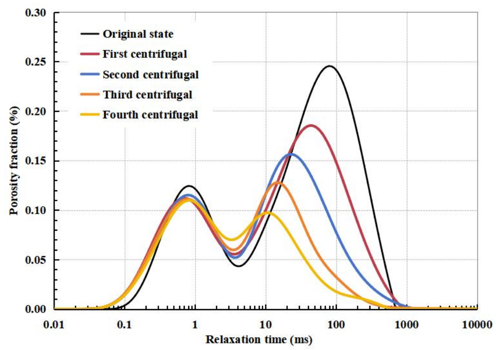

Fig. 3. NMR analysis spectrum of the sample

Physically, the relaxation time T2 represents the size of a pore or a throat in a rock [24], its right and left peaks correspond to the pore and throat sizes, respectively. After multiple centrifugations, the height of the right peak continues to decline, indicating that the water phase in the pores continues to decrease, while the left peak changes very little, indicating that the water phase in the small throat is difficult to be displaced. By combining the HPMI experimental data with the Eq. 3, frequency as a function of capillary/throat radius as shown in the Fig. 4.

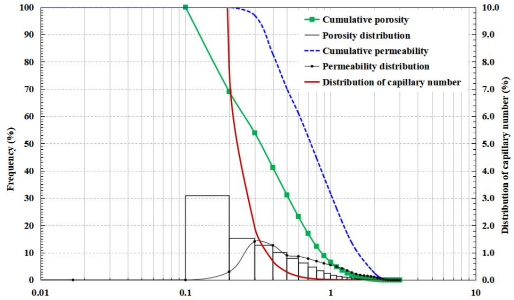

Fig. 4. NMR analysis spectrum of the sample

It can be seen from the figure that in the matrix of the study area, the contribution of capillary/throat with different radii to permeability and porosity is significantly different. 30.89 % of the space in the core is controlled by throat less than 0.1 um. The fluid in this part of the space is difficult to be displaced due to the large capillary force. At the same time, the capillary radius that affects the permeability is mainly concentrated above 0.4 um, while the porosity is mainly controlled by throat with radius of 0.1-1.4 um. This difference will cause a large number of gas in the pores to be blocked by the water phase and difficult to be produced.

3.2 Water Invasion Simulation

In order to deeply investigate the influence of pore throat structure on gas-water co-permeation, the capillary bundle model (Eq. 4-Eq. 8) established for the matrix is used to calculate the theoretical value of gas phase permeability. Also, according to Darcy law, combined with the experimental data of gas flooding water, the gas permeability under different water saturation is obtained, and the data of the two are compared as shown in the Fig. 5.

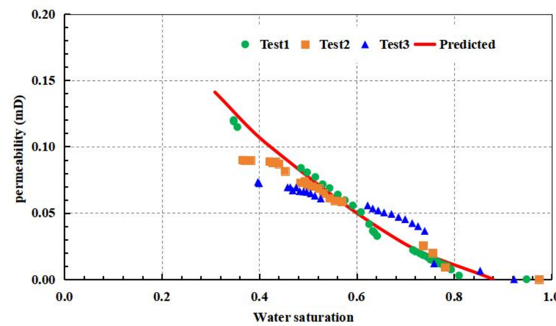

Fig. 5. Gas permeability as a function of water saturation

From the Fig. 5, it can be seen that the fitting relationship between the theoretical value and the experimental value calculated by the established model is preferable. In the matrix, some water phases will gather in small pores and throats and are difficult to be displaced [20-21], and the increase of water saturation will reduce the gas phase permeability.

In order to deeply explore the gas-water seepage and distribution law in the process of water invasion in fractured gas reservoirs, and clarify the development contradiction, a first-line well in the study area was selected as the research object. Based on the geological characteristics of the study area, the edge water gas reservoir is equivalently processed (see Fig.1), and the dynamic data of the well are analyzed in combination with the established mathematical model. Among them, the converted actual bottom hole flow pressure data is used as input data to calculate daily water production and daily gas production as shown in Fig.6:

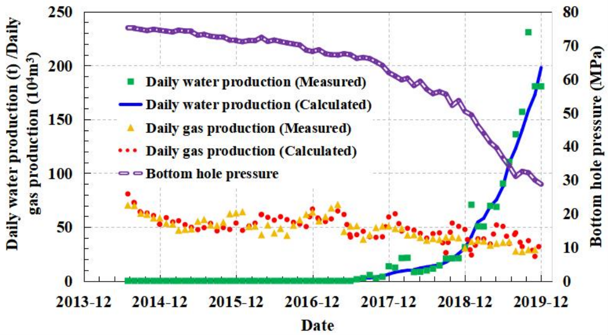

Fig. 6. Measured and predicted data of target well

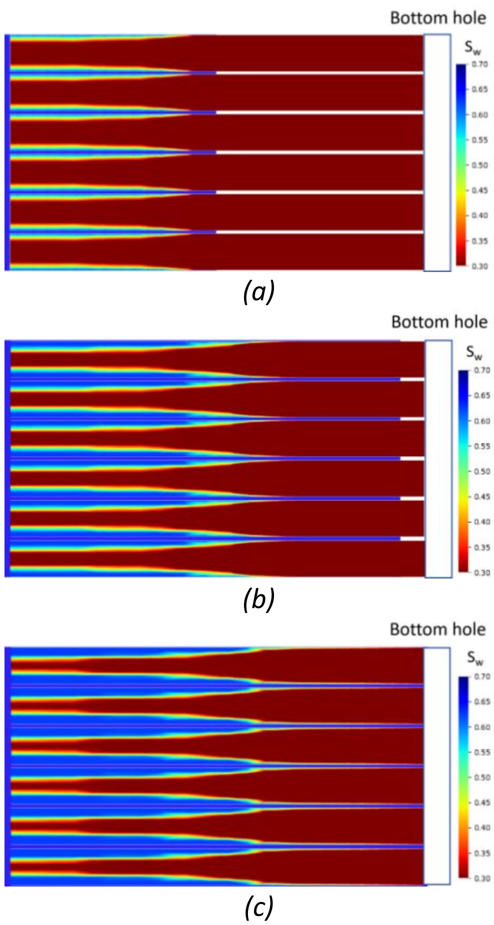

Fig. 7. Equivalent water saturation distribution map of (a) Apr-2016; (b) Apr-2018; (c) Dec-2019

In the early stage of development, there was no water in the production wells, and the bottom hole pressure showed a steady downward trend. However, after water breakthrough, the bottom hole pressure was continuously reduced to ensure the steady of production. However, the bottom hole pressure decreased very fast and reaches 28 MPa by December 2019, also, the water production at the wellbore was very high. It is estimated that the current produced degree is less than 30 %. In order to clarify the distribution of residual gas in the formation, the established mathematical model is used to obtain the equivalent saturation distribution map of the study area at different development times as shown in the Fig. 7.

It can be seen from the figure that with the development of reservoir, the edge water continues to invade the formation along the fractures, the water invasion area gradually expands, and the reservoir water saturation continues to rise.

Because of the strong compressibility of natural gas, the distribution of pressure in the formation is closely related to the distribution of residual gas. Fig. 8 shows the pressure distribution from edge water to production well at different stages of development.

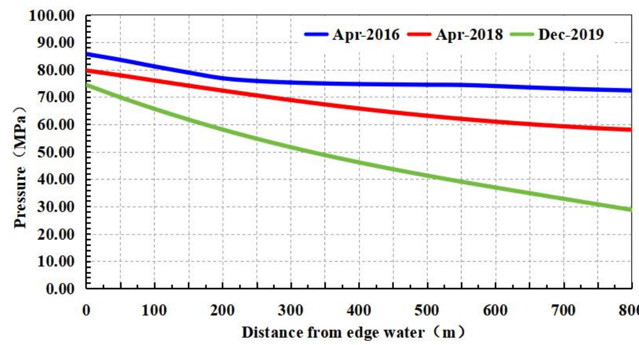

Fig. 8. Pressure distribution from edge water to production well

With the invasion of water phase, the gas single-phase flow in the fracture gradually changes into the gas-water multiphase flow, and the pressure distribution between the edge water and the production well is also changing.

(1) Before the water breakthrough of the production well (see Fig. 6a), the water phase invades the formation along the fracture. At this time, the pressure distribution can be divided into two sections. Near the edge water, because the gas-water two-phase flow is formed in the fracture, the conductivity of the fracture is greatly reduced, the resistance along the path increases, and the pressure drop gradient also increases.

(2) In the early stage of water breakthrough in production wells (see figure Apr-2018), gas-water two-phase flow is formed in fractures from the edge water to the bottom of the production well, and the seepage resistance and pressure drop gradient are further increased. At the same time, due to the influence of water invasion, the gas permeability in the matrix is greatly reduced [10,14], and it is difficult to maintain the existing production under the existing production pressure difference.

(3) In order to ensure the stable production of gas wells, measures to further reduce the bottom hole flowing pressure are adopted, which also aggravates the occurrence of water invasion. The water production at the production well increases rapidly, and the seepage resistance in the fracture also increases further. The gas supply capacity is greatly reduced, and more remaining oil and gas are sealed in the formation and are difficult to be produced.

3.3 Optimization of production strategy

Obviously, in the development of fractured edge-water gas reservoirs, reasonable water control is the key to stable production of gas reservoirs, among which edge drainage and pressure-controlled gas production are common measures [13]. For study area, it is decided to convert the exploration well into a drainage well in the low part of the structure, and maintain the bottom hole pressure of the well slightly lower than that of the production well in the high part, so as to Inhibit the invasion of water. Also, the established numerical model is applied to explore the reasonable production pressure difference that the target well should adopt, that is, the difference between the pressure in the middle of the gas reservoir and the bottom hole flowing pressure. The following figure shows the recovery degree of the gas reservoir under different production pressure differences when the bottom hole pressure reaches the abandonment pressure, which are obtained by using the established model simulation.

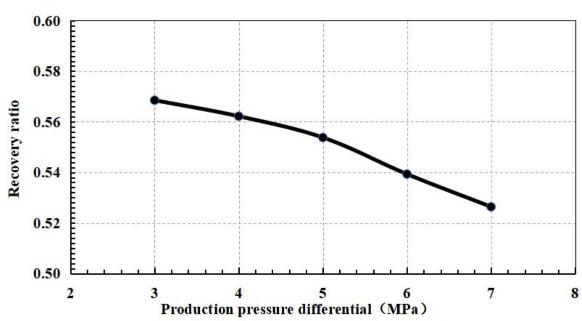

Fig. 9. Production pressure difference optimization

The increase of production pressure difference can improve the gas recovery rate and obtain better economic benefits in the short term, but it also aggravates the occurrence of water invasion and reduces the recovery rate (see Fig. 9). Based on the simulation of the production situation in the study area and the demand of economic development, the optimal production pressure difference should be controlled below 5MPa. Field practice shows that after the edge drainage measures and reasonable production pressure difference are adopted, the bottom hole pressure of the production wells in the study area has rebounded, and the stable production capacity is good. It is expected that the recovery rate can reach more than 50 %. Compared with the previous depletion development, it is expected to increase the recovery rate by more than 15 %.

4. CONCLUSIONS

In this work, the water invasion law and development strategy of fractured gas reservoir have been quantified based on pore throat structure.

A new generalized model is proposed to simulate and evaluate the water invasion law and seepage characteristics in fractured gas reservoirs by combining the capillary bundle model and the dual medium model. So as to lay the foundation for more effective and efficient development of gas reservoirs.

(2) The water invasion phenomenon will make the gas phase permeability decreased seriously, and a large number of remaining gas is closed in the pores, which is difficult to be produced. The production mode of reducing the bottom hole pressure and increasing the production pressure difference can maintain the production in a short time, but it will make the water invasion phenomenon more serious and greatly reduce the recovery degree of the gas reservoir.

(3) Reasonable water control is the key to stable production of fractured edge water gas reservoir. On the basis of edge drainage, the gas reservoir can be developed more efficiently by maintaining reasonable production pressure difference. The simulation results and field practice show that the reasonable production pressure difference in the study area should be controlled within 5MPa, and the targeted production measures can improve the recovery rate of gas reservoir by more than 15 %.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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