Research on Seepage Characteristics at Rock Core Scale of Tight Sandstone Gas Reservoir

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Abstract

With respect to the special seepage rules of tight sandstone gas reservoir which is different from conventional gas and its non-linear seepage characteristic, this paper takes Sulige block as the research object, analyzes the influence of seepage characteristics on capacity from aspect of seepage characteristic experiment, and manifests the gas-water flow condition of tight sandstone gas reservoir with stress sensitivity coefficient, starting pressure gradient, permeability jail, relative permeability curve, etc. The results show that the water saturation has a much greater influence on gas phase flow in tight sandstone than the gas phase flow in medium and high sandstone; the change of porosity and permeability has a significant influence on permeability jail; the target block has a stress sensitivity which is stronger at the beginning of effective stress loading, greatly damaging the permeability.

Keywords

Seepage characteristic; tight sandstone; starting pressure; stress sensitivity.

1. Preface

China is abundant in tight sandstone gas reservoir which has a great exploitation potentiality. With development of economy and advance of science and technology, the low-permeability gas reservoir is playing a more and more important role in optimizing China's energy structure, guaranteeing energy safety, developing natural gas industry, etc. The enhancement for exploitation and use of tight sandstone gas reservoir appears to be particularly important for gradually increasing the proportion of natural gas in China's energy structure, strengthening energy self-sufficiency of China, reducing the foreign-trade dependence of petroleum, and other petroleum strategies. The tight sandstone gas reservoir has complex geological conditions, and it is featured of low porosity and permeability, high water saturation, strong heterogeneity, strong stress sensitivity, high capillary entry pressure, etc., which has different degrees of influence on gas seepage, shows special seepage rules which are different from conventional gas, and has characteristics of non-linear seepage.

Foreign scholars began to research the gas-water seepage very early had got a large amount of research achievements [1-12]. In 2011, Fan Zhaowei et al [13] conducted research on phase seepage with volcanic gas reservoir as object. It had main features of high irreducible water content, small co-permeation zone of gas phase and water phase and low relative permeability of gas phase at irrducible water content. Guo Ping (2015) [14] carried out high temperature and high pressure gas-water seepage experiment for tight sandstone reservoir, and the co-permeation zone of gas phase and water phase on seepage curve of gas phase and water phase under conditions of high temperature and high pressure was much larger. Hu Yong (2016) [15] took tight reservoir rock core of Sulige gas field as research object and indicated that the permeability of gas phase was greatly influenced by the permeability of rock sample. Currently, most permeation test of gas phase and water phase adopt a regular method according to GB/T28912-2012 Test Method for Relative Permeability of Water Phase and Gas Phase in Rock [16]. This paper takes Sulige block as research object, analyzes the influence degree of seepage characteristic on capacity from aspect of seepage characteristic experiment, and provides theoretical basis and technology support for effective exploitation of Sulige block.

2. Indoor experiment of rock core seepage characteristic

Due to low porosity, poor seepage capacity and complex pore structure of tight sandstone gas reservoir, the gas-water seepage does not follow the basic Darcy seepage law anymore. Domestic and foreign scholars believe that the tight sandstone gas reservoir has permeation characteristics of permeability jail, starting pressure gradient, stress sensitivity, etc., therefore, this paper conducts indoor experiment evaluation according to reservoir classification of Sulige block [17].

Tab.1 This paper conducts indoor experiment evaluation according to reservoir classification of Sulige block

Classification of Reservoir	Porosity(%)	Permeability(mD)	Reservoir thickness(m)
Class I	≥10	≥0.41	≥5
Class II	7~10	0.19~0.41	3~5
Class III	5~7	0.02~0.19	<3

2.1 Seepage curve experiment of gas-water phase

According to the experimental requirements in national standard [16], the rock core permeability of tight sandstone gas reservoir is generally less than 1mD, so this paper adopts the method of unstable state experiment, and the specific experimental procedure is as follows:

(1) Record the experimental temperature and atmospheric pressure, and select the initial pressure difference according to $\pi_1 \leq \triangle P \leq \pi_2$. The formula of calculating π_1 and π_2 is as follows:

$$\pi_1 = 0.00167\sigma\sqrt{\frac{\phi}{K_\infty}} \tag{1}$$

$$\pi_2 = 0.00002\frac{L\sigma}{K_\infty} \tag{2}$$

Where: L is the length of rock sample, cm;

σ is the surface tension of nitrogen, mN/m;

ϕ is the porosity of rock sample, %;

K_∞ is the gas-measuring Kirschner permeability, μm^2:

π_1 and π_2 are the pressure reference values for determining the initial displacement pressure, Mpa.

(2) Take out the rock sample of saturated and stimulated formation water, wipe off the fluid on the surface of rock sample with absorbent gauze wet with saturated and stimulated formation water, and measure the wet weight of rock sample using electronic scale immediately. Put it into the rock core holder. The direction of rock sample is the same as the direction of measuring Kirschner permeability.

(3) Adjust the output pressure of high pressure nitrogen cylinder and the output pressure of gas booster pump according to the selected pressure difference, and increase the confining pressure of rock core holder to a level which is 8MPa higher than the selected upstream pressure.

(4) Record the initial value of wet-type flowmeter and gas-water separator, record the selected upstream pressure and confining pressure, and adjust the initial value of gas flowmeter to 0 and the cronometro to 0.

(5) Connect the output nitrogen of holder upstream gas booster pump, and press the cronometro at the same time.

(6) Accurately record the cumulative time of gas producing and water producing, and the cumulative time, cumulative gas production and cumulative production corresponding to each moment of gas producing and water producing. In case of flow rate more than 0.6ml/s, use the wet-type flowmeter to measure the cumulative gas production.

(7)When water yield reduces significantly and the cumulative water production in separator at 15-20 min interval does not increase, disconnect the upstream nitrogen and stop the cronometro at the same time, then empty the residual pressure at the wellhead side of holder.

(8) Remove the confining pressure, take out the rock sample, and weigh it using electric scale which accurate to four decimal places. Calculate the water saturation and cumulative water production of rock sample at this moment, the formula is as follows:

$$W_n = \frac{m_{\text{wet}} - m_n}{\rho} \tag{3}$$

$$S_w = \frac{m_n - m_{\text{dry}}}{\rho V_p} \times 100\% \tag{4}$$

Where: m_{dry} and m_{wet} are the mass of rock sample before and after saturation and simulation formation water respectively, g;

m_n is the mass of rock sample at time of t_n, g;

S_w is the water saturation of rock sample, %;

W_n is the cumulative water production within t_n, ml;

V_p is the pore volume of rock sample, cm3.

(9) Put the rock sample into the holder again, and increase the confining pressure to a level which is 2MPa higher than the selected upstream pressure. Connect the output nitrogen of holder upstream gas booster pump, and press the cronometro at the same to start.

(10) After 20-30 minutes, disconnect the upstream nitrogen and stop the cronometro at the same time. Empty the residual pressure at the inlet side of holder. Repeat the above two steps until the water saturation change of rock sample between two adjacent measurements is less than 2%.

(11) Lengthen the displacement time between measurements until the rock sample is in a state of irreducible water. Measure the gas permeability of rock sample in the state of irreducible water at displacement pressure and 1/2 displacement pressure respectively.

(12) Adjust the output pressure of gas booster pump to 0, close the main valve of high pressure gas, empty the gas and liquid of all pipes and connecting components of instrument, and clean the gas-water separator and rock core holder.

(13) Turn off all powers of instrument, fully check the lab safety and then finish the experiment.

2.2 Stress sensitivity experiment

The stress sensitivity of reservoir is a phenomenon that the permeability of oil and gas reservoir changes as the effective stress changes. The effective stress is usually defined as the difference between the burden pressure and fluid pressure. In combination with the actual situation that most gas wells have begun to produce water in the exploitation process of Sugeli gas field, in the experiment of research on the influence of rock core stress sensitivity on gas-water phase permeation, this paper measures the relative permeability with variable confining pressure and studies the influence of different effective stresses on effective permeability.

The specific method is to dry the rock core and then weigh it, vaccumize the saturated formation water for 24 hours, and keep the fluid pressure at the inlet side and the return pressure at the outlet side unchanged. It must ensure that the initial pressure difference can not only overcome the end effect, but not produce turbulent flow. The internal pressure does not change in measurement. Increase the confining pressure gradually, measure the gas phase and water phase permeability at each pressure point, record the displacement time, displacement pressure difference, cumulative fluid production, cumulative water production and initial gas-producing point at each moment. When the gas-driving water reaches to a state of irreducible water, measure the gas permeability, and get the designed max effective stress of 25MPa.

With the stress sensitivity experimental method of variable confining pressure, it measures the permeability change of rock core at effective stress of 8MPa, 15MPa, 20MPa and 25MPa. Based on industrial standard (SYT 5358-2010 Reservoir Sensitivity Flow Experimental Evaluation Method), it calculates the permeability damage coefficient according for formula (5). The experiment results are shown in Table 2-5, and the expression of permeability damage coefficient is as follows:

$$D_{b_y} = \frac{K_i - K_{i+1}}{K_i \left| P_{i+1} - P_i \right|} \tag{5}$$

Where: Dkp is the permeability damage coefficient, MPa−1；

Ki is the permeability of rock sample at effective stress i, 10−3μm2；

Ki+1 is the permeability of rock sample at effective stress i+1,10−3μm2；

Pi——is effective stress i, MPa；

Pi+1——is effective stress i+1, Mpa.

2.3 Starting pressure gradient experiment

Starting pressure gradient is the pressure gradient value corresponding to the crosspoint of reverse extension of straight line on one pressure square gradient curve and pressure square gradient axis, it manifests the average pressure gradient to be overcome by fluid when flowing in rock core, which is also the seepage resistance to be overcome when passing the pole canal of average size. The experimental procedure is as follows:

(1)Dry the rock core for 48 hours, measure the length, diameter, mass and gas permeability of rock core, vacuumize the saturated standard saline of rock core, weigh it and calculate the effective porosity;

(2)Put the rock core into the rock core holder, and apply confining pressure slowly at a step length of 1MPa and interval of 20min. Apply to the actual burden pressure and stop to keep constant, increase the experimental temperature to 60°C, connect the procedure, set the initial value of instrument to zero, and displace the rock core with nitrogen until the water saturation does not change anymore;

(3)Fill the intermediate container with simulated gas and apply pressure to the original reservoir pressure, set the return pressure to reservoir pressure, open the inlet valve of rock core holder, and expose the rock core to simulated gas for 30min to displace the nitrogen in rock core. Close the inlet valve, slowly lower the return pressure to dew point pressure, critical flowing pressure and flowing bottomhole pressure and keep stable. Observe the gas production at the outlet until the outlet does not product gas for 12 hours anymore;

(4)Put the fine tube of holder outlet under the liquid level of collection device, open the outlet of intermediate container which is full of high pressure nitrogen, then open the inlet valve of holder, and adjust the pressure regulating valve to increase pressure slowly;

(5)Observe the outlet under the liquid level until the first bubble appears, close the inlet valve of rock core holder, keep the upstream and downstream pressure data unchanged until the pressure keeps stable for 48 hours.

2.4 Method of identifying the permeability jail

Permeability jail means a certain water saturation range in tight reservoir. Within this range, the gas-water phase permeation capacity is extremely weak, and it is difficult to realize effective flow. The existence of permeability jail greatly restricts the production of tight gas and effective exploitation of tight sandstone gas reservoir. The identification procedure of permeability jail is as follows:

(1) Determine γ, λg and λw. Draw the relative permeability curve of low-yield well rock core in research area, and calculate the proportion of permeability and porosity of all rock cores; make statistics of the relative permeability of isotonic points on relative permeability curve and the curvature at turning point on gas-water phase relative permeability curve; draw the isotonic relative permeability, the curvature at turning point on gas phase relative permeability curve, the curvature at turning point on water phase relative permeability curve and the permeability/porosity (K/ϕ) relationship, accordingly identify the concentration area of isotonic relative permeability, curvature at turning point on gas phase relative permeability curve and curvature at turning point on water phase relative permeability curve, and the upper limit of concentration area is γ, λg and λw.

(2) Identify if the isotonic relative permeability of tight sandstone gas reservoir rock core meets the constraint conditions of isotonic relative permeability. If yes, go to step 3, or the rock core has no permeability jail.

(3) Calculate the water saturation at the left and right boundary of permeability jail. If $Swjl<Swjr$, then the rock core relative permeability curve has permeability jail, and the water saturation of permeability is Swjl~Swjr, if $Swjl>Swjr$, then the rock core relative permeability curve has no permeability jail.

3. Percolation characteristics analysis of rock core

3.1 Gas-water two-phase permeability curve

Relative permeability curves were all downward concave, and gas phase relative permeability was very low. The water saturation of isotonic point is about 76%, the saturation of bound water was 62.11%, and the water saturation of gas-water co-permeability zone was about 65.90%-96.21%. With the increase of water saturation, gas phase declined rapidly, while water phase relative permeability began to rise slowly and then increased rapidly, indicating that when water appeared in a gas well, the productivity loss of the gas well was obvious and the gas well was prone to liquid accumulation. With the increase of water saturation in pore, gas phase permeability of tight sandstone reservoir would decrease sharply.

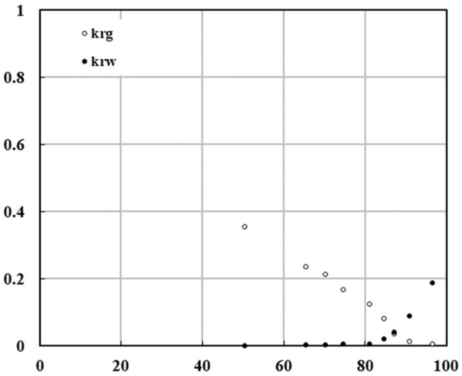


Fig. 1 Gas-water Two-phase Seepage Curve

It was obviously unreasonable to choose the relative curve of a rock sample as the representative of the whole gas reservoir and apply it to the calculation of gas reservoir engineering and numerical simulation. Because rock samples for core analysis had different permeability and porosity, the relative curves measured were different. Therefore, according to the characteristics of gas reservoirs and different permeability, several parameters were selected: The representative relative curve was normalized on this basis to obtain the mean relative curve that could represent the gas reservoir.

Gas-water standardized relative permeability was defined as follows:

$$K_{rw}^{*}=\left(S_{w}^{*}\right)^{a} \tag{6}$$

$$K_{rg}^{*}=\left(1-S_{w}^{*}\right)^{b} \tag{7}$$

Of Which:

$$K_{rw}^{*}=K_{rw}\big/K_{rw}\left(S_{gr}\right) \tag{8}$$

$$K_{rg}^{*}=K_{rg}\big/K_{rg}\left(S_{wi}\right) \tag{9}$$

$$S_{w}^{*}=\left(S_{w}-S_{wi}\right)\big/\left(1-S_{wi}-S_{gr}\right) \tag{10}$$

The relationship between the logarithm of gas-water standardized relative permeability and effective wet saturation could be obtained by taking the logarithm of both sides of the above equation respectively.

$$LgK_{rw}^{*}=aLgS_{w}^{*} \tag{11}$$

$$LgK_{rg}^{*}=bLg\left(1-S_{w}^{*}\right) \tag{12}$$

Which were derived as:

$$K_{rw}=K_{rw}^{*}\cdot K_{rw}\left(S_{gr}\right) \tag{13}$$

$$K_{rg}=K_{rg}^{*}\cdot K_{rg}\left(S_{wi}\right) \tag{14}$$

$$S_{w}=S_{w}^{*}\left(1-S_{wi}-S_{gr}\right)+S_{wi} \tag{15}$$

Where, K_{rw}^{*}, K_{rg}^{*} -- Represent standardized water and gas relative, decimals;

K_{rw}, K_{rg} , -- represent relative permeability of water and gas, decimals;

$K_{rw}\left(S_{gr}\right)$, $K_{rg}\left(S_{wi}\right)$ -- Respectively represent relative permeability of water under residual gas saturation and relative permeability of gas under bound water saturation, decimals;

S_{w}, S_{wi}, S_{gr} -- Respectively represent water saturation, irreducible water saturation, residual gas saturation, decimals;

S_{w}^{*} -- standardized water saturation, decimals;

a, b -- constants that depend on pore structure and wettability.

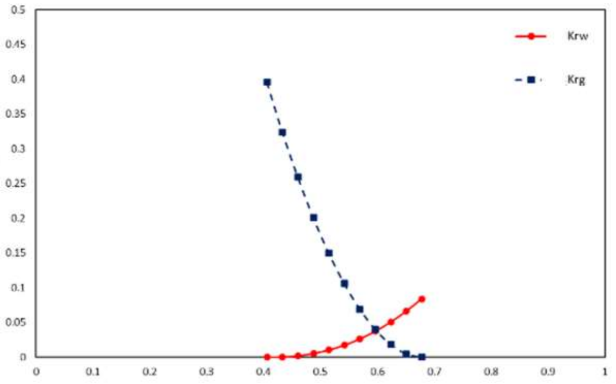


Fig. 2 Change curve of standardized gas-water two-phase relative permeability in Class I reservoir

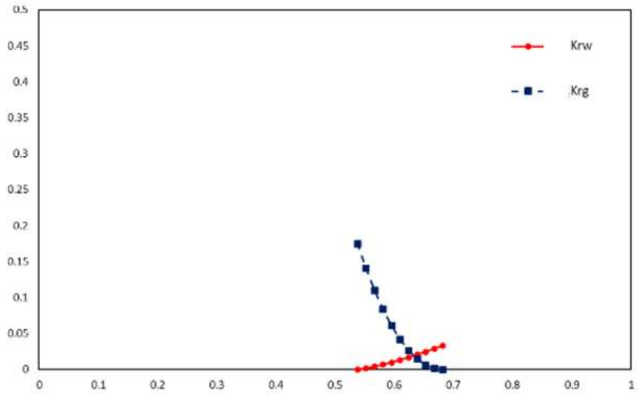


Fig. 3 Change curve of standardized gas-water two-phase Relative permeability in Class II reservoir

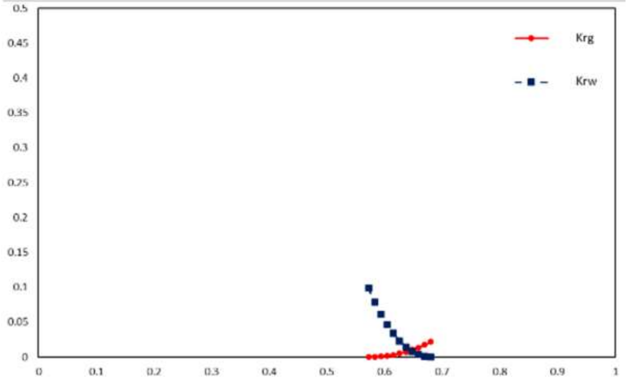


Fig. 4 Change curve of standardized gas-water two-phase relative permeability in Class III reservoir

As could be seen from the figure, the influence of water saturation on gas phase flow in tight sandstone was far greater than that in medium-high permeability sandstone. With the decrease of permeability and permeability, the co-permeability point and bound water saturation moved to the right, and the co-permeation zone became narrower.

3.2 Stress sensitivity

According to the experimental method of stress sensitivity test under variable confining pressure, a rock core of Class I, CLASS II and class III in Well Su 59 was gas measured. Test the change of rock core when the burden stress was 2MPa, 5MPa, 12MPa, 25MPa and 40MPa.

With the increase of burden stress, all three types of reservoirs showed certain stress sensitive damage, and the following formula was used to calculate the stress sensitive coefficient.

$$K = \mathrm{k}_0 e^{-\alpha_k (p_0 - p)} \tag{16}$$

Where: k0 -- initial permeability of rock core, mD;

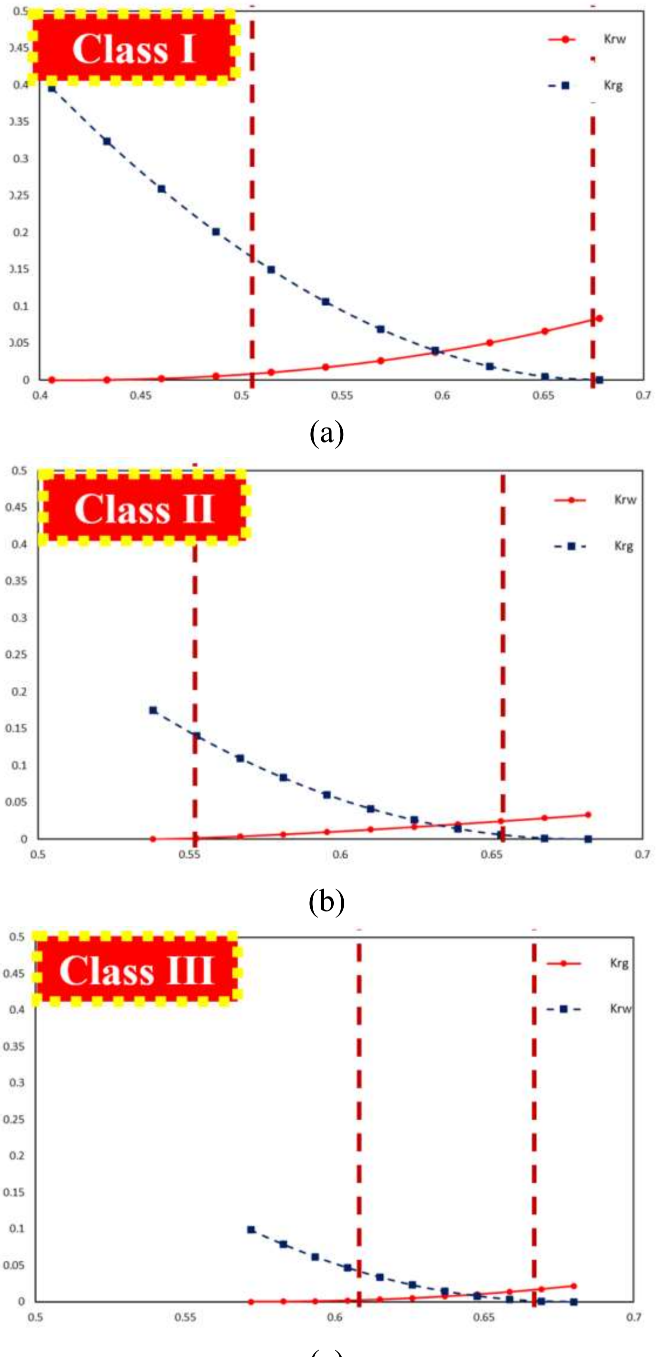
α_k --Stress sensitivity coefficient, decimal;

P0-- Original burden stress, MPa;

P -- Experimental burden stress, MPa;

The stress sensitivity coefficients of I, II and III reservoirs were 0.211, 0.2687 and 0.723, respectively. This indicated that rock core of Sulige Gas field had strong stress sensitivity. Therefore, at the initial stage of effective stress loading, the stress sensitivity was strong and the damage was large. The analysis showed that the contraction of pores and pore channels in rock core could be approximately seen as circular pores. When the effective stress was small, the sharp contraction of pore channels after compression led to the decrease of rock core seepage capacity, which was represented by the decrease of permeability value. However, when the force around the circular pore channel reached a certain value, it became difficult to make the channel further shrink, which was manifested as the reduction range of permeability decreased and gradually tended to a constant value. Therefore, the gas-water effective permeability did not change much at this time.

3.3 Permeability jail characteristics



(a)

(b)

(c)

Fig. 5 Gas pressure square gradient-flow velocity relation graph

As could be seen from the figure, with the decrease of porosity and permeability, the range of permeability jail was concentrated in the co-permeability area, and the left limit of permeability jail gradually moved to the right, that was, the higher the water saturation was, the more prone the prison-seepage phenomenon would occur. Therefore, it was believed that there was a certain permeability jail in the reservoir of this block.

4. Conclusion

1. In order to study gas-water permeability of tight sandstone gas reservoir, stress sensitivity coefficient, threshold pressure, permeability jail and phase permeability curve were used to characterize the flow state of gas-water and gas reservoir of tight sandstone.

2. According to the normalized phase permeability curve, the influence of water saturation on gas phase flow in tight sandstone was far greater than that in medium-high permeability sandstone. With the decrease of permeability and permeability, the co-permeability point and bound water saturation moved to the right, and the co-permeability zone became narrower.

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