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Analysis of the influence factors of tight reservoir start-up pressure difference

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Abstract. Tight gas reservoir is not only characterized by low permeability, but also by high water saturation. This paper was studied on the basis of tight reservoir microscopic pore structure analysis, through gas depletion-drive development simulation experiments of constant rate production and constant pressure difference two ways, analyzed the influence factors of reservoir starting pressure difference, to explore the change law of tight reservoir start-up pressure. The study suggests that the pore structure throat radius of tight reservoir is small, and the throat occupies a large proportion of pore volume, and the throat is not only the seepage channel but also the important storage space. The experiment also shows that the throat radius, water saturation and effective stress are the main factors to determine the starting pressure difference of reservoir. So in the development process, some measures have been taken to reduce or control the start-up pressure near wellbore area such as well location optimization, perforating optimization, increasing fracturing fluid flowback rate and drainage gas recovery measures optimization, these measures have achieved positive effect in Sulige gas field.

1. Introduction

Since 1970s, the United States has developed tight gas resources and it has the most mature technologies of tight sandstone gas development. In 2008, the tight gas production reached $1757 \times 10^8 \text{ m}^3$, which accounted for more than 30% of the total gas production [1]. The tight gas geological resources in China is about $17.4 \times 10^{12} \text{ m}^3 \sim 25.1 \times 10^{12} \text{ m}^3$ [2]. And such resources in the Ordos basin is approximately $10.37 \times 10^{12} \text{ m}^3$, which mainly distributes in Sulige and Shenmu gas field in the north of the basin [3]. Now the development of tight gas has formed a certain scale. In 2013, the tight gas production exceeded $200 \times 10^8 \text{ m}^3$, and the output reached 2/3 of the total gas production.

The discovery and successful development of tight gas reservoirs show a great prospect of the development of tight gas, and also reveal the complexity of geological conditions and the difficulties in development. Taking Sulige gas field as an example, there are many main problems, the difficulty in evaluation of multi-layer overlapping production capacity, large difference in evaluation of static parameters and dynamic parameters, low recovery efficiency, unclear remaining reserves distribution and so on [4-7]. A large number of previous studies show that low permeability reservoir has the starting pressure, which has a great influence on the recovery of oil and gas reservoirs and the distribution of remaining reserves[8-11]. Therefore, it is necessary to clarify the influence degree of different reservoir characteristics on starting pressure, to establish reservoir classification evaluation



method matches with gas wells production, to optimize the well spacing of multi-layer gas reservoirs, to continuously improve the recovery rate, and to realize long-term stable production of gas field.

In this paper, we analyzed the micropore structure of reservoir, carried out the experiment of starting pressure difference with different physical properties and different water saturation, then analyzed the influence factors of the starting pressure difference of the reservoir, which provides a theoretical basis for further optimizing the start pressure gradient measurement and classified evaluation of tight reservoir.

2. Microscopic characteristics of tight sandstone reservoir

Although the oil&gas industry uses porosity and permeability distribution to determine whether the gas reservoir belongs to the tight gas reservoir, but both can not really reflect the difference between tight reservoir and conventional reservoir, and it also can not reflect how this difference affects the development of natural gas and even the formation of gas reservoirs.

Rate-controlled mercury penetration experiment can distinguish the throat from the pore, can measure the pore radius and throat radius distribution respectively, so the pore throat ratio parameters can be obtained [12]. We compared the structure of different physical reservoirs with the results of rate-controlled mercury penetration experiment, clarified the difference of pore microscopic characteristics, which provide basis for starting pressure difference analysis. The experimental analysis of the rate-controlled mercury penetration of 20 different physical reservoir cores shows that the tight reservoir has the following characteristics compared with the low permeability reservoir:

(1) Complex porosity and permeability relationship of tight reservoir.

The textural maturity level and compositional maturity level of tight sandstone reservoir are low, the diagenesis evolution is complex, and the correlation between reservoir porosity and permeability is poor. The main gas reservoir He 8 layer of Sulige gas field affected by the sedimentary source and hydrodynamic power, its rock types include lithic quartz sandstone, lithic sandstone, quartz sandstone and so on. Sandstone grain size vary from fine sand to fine gravel, the composition is complex and the structure is different. The porosity is widely distributed under the influence of diagenetic compaction and dissolution(Figure1), from 5% to 20%. However, the permeability is generally lower, which is less than $1.0 \times 10^{-3} \mu\text{m}^2$, under the condition of gas reservoir, it is less than $0.1 \times 10^{-3} \mu\text{m}^2$. The relationship between reservoir porosity and permeability is complex. With the increase of the porosity, the permeability increases slightly, the correlation is poor. However, the pore and permeability correlation of DH low permeability sandstone gas reservoir is very good.

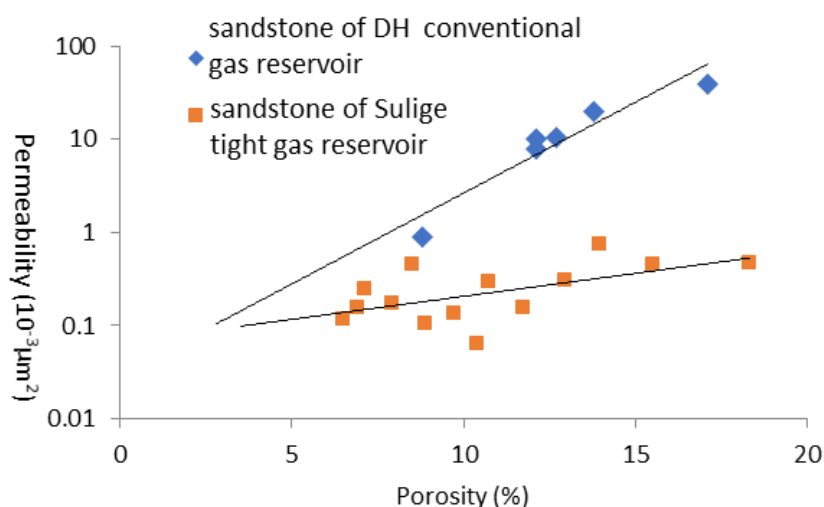


Figure 1. The porosity and permeability relational graph of different lithologic reservoirs.

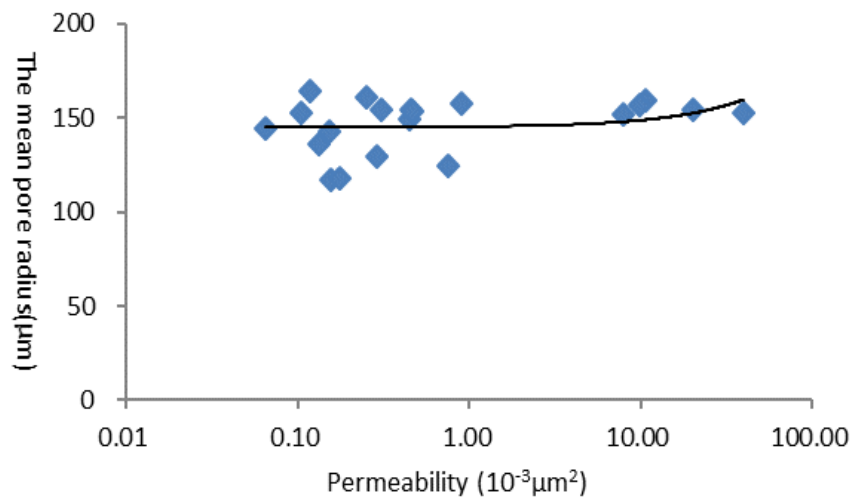


Figure 2. The relational graph of the permeability and the average pore radius.

(2) Great difference of throat radius between the tight reservoir and the conventional reservoir

By comparing the average pore radius of different permeability reservoirs (Figure 2), it can be seen that the permeability is not necessarily related to the average pore radius. Whether in the tight reservoir with the permeability less than $1.0 \times 10^{-3} \mu\text{m}^2$, or in the low permeability reservoir with the permeability greater than $10 \times 10^{-3} \mu\text{m}^2$, all the pore radius are between 116-164 μm , and the average is 146.6 μm , there is no statistical difference between the tight reservoir and the low permeability reservoir.

Comparing the average throat radius of different permeability reservoir can be seen that the permeability is consequently related to the average throat radius. The low permeability reservoir with the permeability greater than $10 \times 10^{-3} \mu\text{m}^2$, its radius is greater than 3.0 μm , and the tight reservoir with the permeability less than $1.0 \times 10^{-3} \mu\text{m}^2$, its radius is between 0.54-0.99 μm , the average is 0.74 μm . The difference is obvious. Compared with the pore structure of low permeability reservoir, the tight reservoir is mainly characterized by a smaller throat radius. (Figure 3)

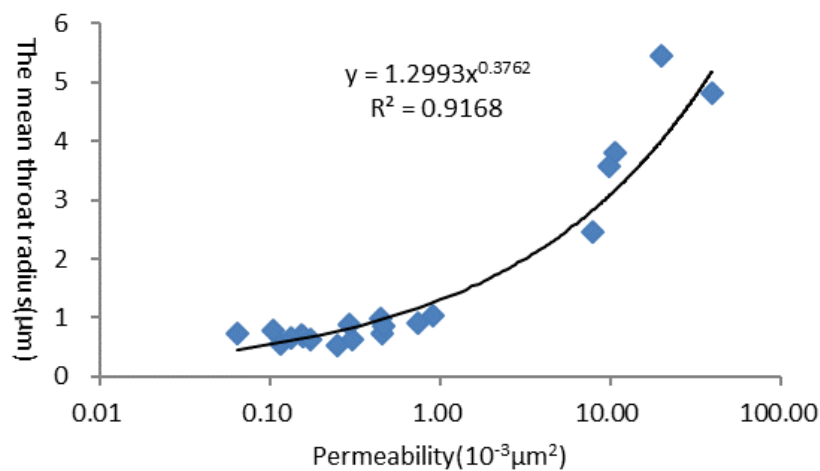


Figure 3. The relational graph of the permeability and the average throat radius.

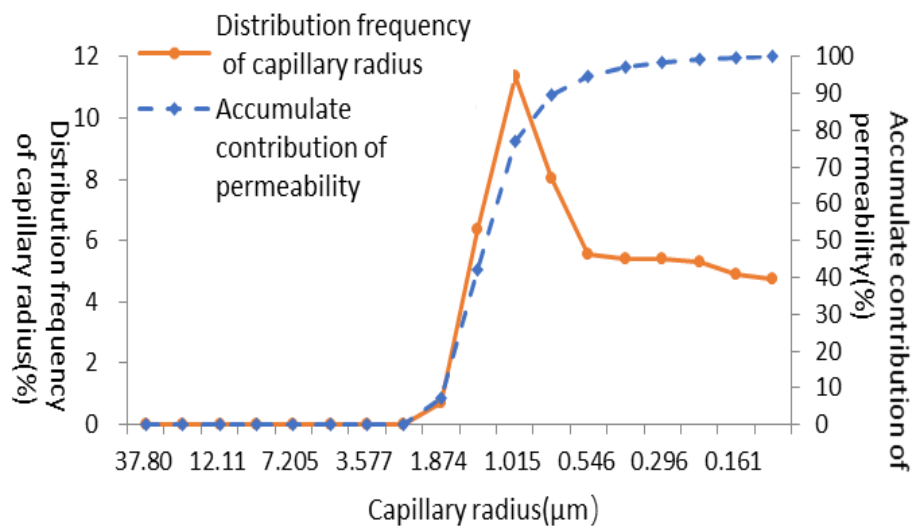


Figure 4. Distribution of capillary radius and its accumulate contribution to permeability.

(3)The permeability of tight reservoir is mainly contributed by the minority throat with a larger radius.

The throat radius of tight reservoir is widely distributed. Take the core specimen from Sudong block He 8 layer(Figure 4), the permeability is 0.46mD, the pore is 15.52%, the largest capillary radius is 1.874μm, the main throat radius is 1.169μm, the main throat radius lower limit is 1.015μm. The throat radius larger than 0.74μm accounted for 26.5%, while the permeability contribution reached 90%.

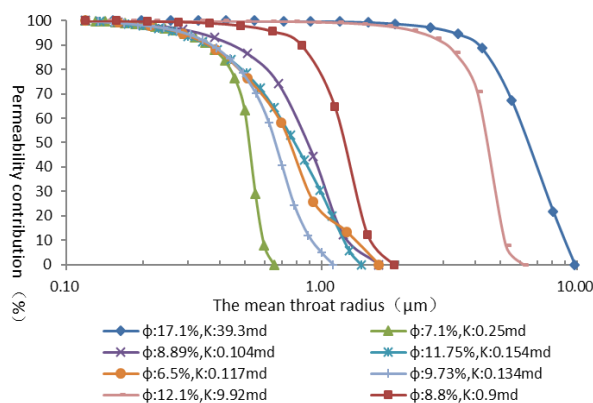


Figure 5. The graph of permeability contribution rate of different physical reservoirs.

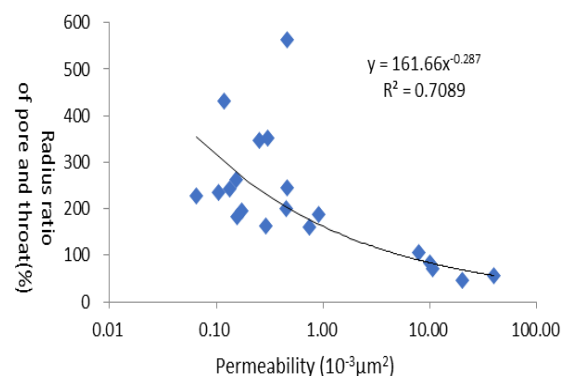


Figure 6. Diagram of relation between reservoir permeability and radius ratio of pore and throat.

The radius of main throat in different permeability reservoirs varies greatly (Figure 5), the low-permeability reservoir with a permeability greater than 10 mD, its 90% of the permeability is contributed by the throats which radius are greater than 4μm, and the tight reservoir with a permeability smaller than 1.0mD, its 90% of the permeability is contributed by the throats greater than 0.5μm.

(4)The pore throat radius ratio of tight reservoir is large

Comparing the mean value of pore throat radius of different permeability reservoirs (Figure 6), it can be seen that there is an obvious relationship between the permeability and the average value of the pore throat radius. The radius ratio of pore throat in a low permeability reservoir with a permeability greater than 10 mD is less than 100, while the radius ratio of pore throat in dense reservoirs with a permeability of less than 1.0mD is between 161 and 563, with an average value of 274, indicating a significant difference.

(5)The throat volume of tight reservoir accounts for a high proportion of total pore volume

Comparing throat volume proportion of different permeability reservoir can be seen (Figure 7) that the low permeability reservoir with the permeability greater than 10mD, its throat volume accounts for less than 40% of total pore volume, and the dense reservoir with the permeability less than 1.0 mD, its throat radius ratio is between 37.6-97.6%, average 67.8%, suggesting that throat for dense reservoir is not only an important seepage channel but also an important storage space.

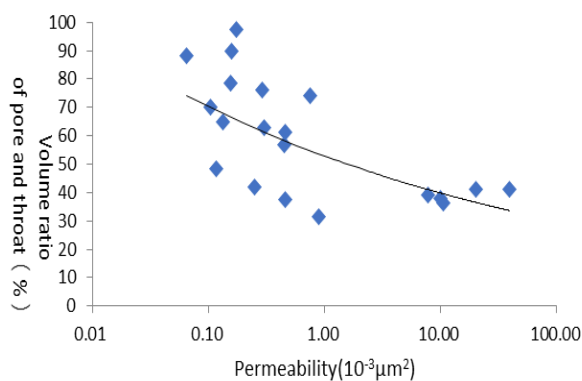


Figure 7. Diagram of relation between reservoir permeability and throat volume.

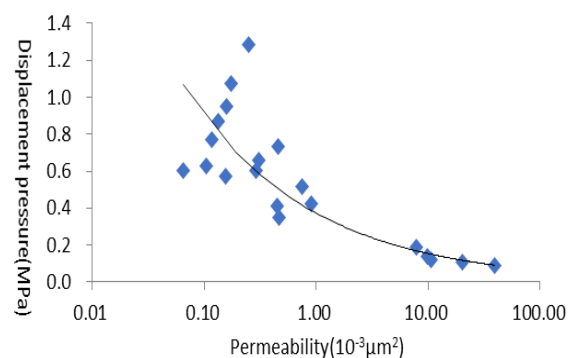


Figure 8. Diagram of reservoir permeability and displacement pressure.

(6)The displacement pressure of dense reservoir is high and rises rapidly with the deterioration of physical properties

Comparing different permeability reservoir displacement pressure can be seen (Figure 8) that there is significant negative correlation with displacement pressure and permeability, the low permeability reservoir with the permeability greater than 10mD, its displacement pressure is less than 0.2MPa, average 0.13MPa, while the dense reservoir with the permeability less than 1.0 mD, its displacement pressure is between 0.34-1.28MPa, average 0.7MPa.

Overall, compared with the low permeability reservoir, the density reservoir pore structure throat radius is generally small, but the pore volume controlled by micro throat is large. The throat is not only a seepage channel but also an important storage space.

3. Influencing factors analysis of starting pressure difference

In recent years, many starting pressure experiments have been carried out for tight sandstone reservoirs, however, the conclusions from different experiments are quite different. this paper by analyzing the influencing factors of starting pressure difference, deeply analyzes the internal causes of starting pressure difference.

3.1. The relationship between starting pressure and reservoir properties

According to the data of closed core extraction, the water saturation of tight sandstone reservoirs in He 8 of Sulige gas field is mainly between 30% and 65%, gas wells with different physical properties and different water saturation show very strong differences, especially in single well production, production decline rate and recovery rate. In order to study the influence of reservoir physical properties and water saturation on the development of tight gas reservoirs, depletion-drive

development physical simulation experiment was carried out for different physical reservoirs and different water saturation reservoirs. And for reducing the error caused by the test measurement and better simulating the process of gas reservoir development, long core samples were obtained by using the same physical core series combination method in the experiment.

Four groups of rock samples starting pressure difference with water saturation of about 50% was selected, as can be seen from figure 9, the starting pressure difference increased significantly with the decrease of permeability. Especially when the permeability is less than 0.5mD, the start-up pressure difference increases rapidly.

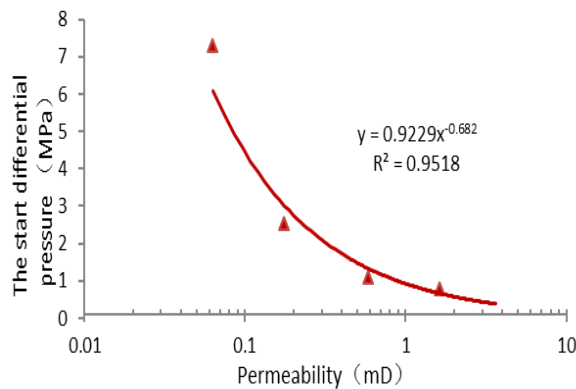


Figure 9. Permeability and start differential pressure diagram.

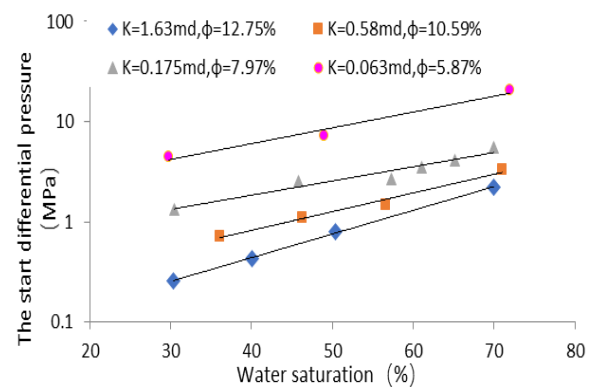


Figure 10. Water saturation and start differential pressure diagram.

According to the analysis, Jamin effect is the main cause of starting pressure difference in the reservoir. The size of Jamin effect is shown in equation 1 and is mainly affected by pore throat ratio.

$$\Delta p_c \approx 2\sigma_{1,2} \cos \theta_{1,2} \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (1)$$

In the formula, Δp_c is the additional resistance effect (Jamin effect), MPa; $\sigma_{1,2}$ is the interfacial tension of gas and liquid, mN/m; $\theta_{1,2}$ is gas-liquid two phase contact angles; R_1 is the radius after the bubble is deformed, m; R_2 is the radius before the bubble deforms, m.

The pore radius determine the size of the bubble (due to the small thickness of water film, the influence of water film on bubbles can be ignored), the radius before the bubble deformation can be approximately considered as the pore radius, the radius after the bubble deformation can be approximately considered as the throat radius. The minimum gas-liquid two phase contact angles in the process of bubble deformation is 0° , and the pore throat radius ratio in tight reservoir is greater than 100, therefore, equation 1 can be simplified to equation 2.

$$\Delta p_c \approx 2\sigma_{1,2} \frac{1}{R_1} \quad (2)$$

So in the tight sandstone reservoir, except the factors can affect the gas-liquid interfacial tension, such as fluid properties, formation pressure, temperature and so on, the throat radius is the main factor of reservoir starting pressure difference.

3.2. The relationship between starting pressure and water saturation

The gas seepage laws of the same rock sample under different water saturation are different[13]. Combined with the lower limit of physical property of tight sandstone gas reservoir in Sulige gas field, three groups of rock samples with the permeability more than 0.1mD were selected for starting pressure experiments under 14 different physical properties and water saturation conditions. As shown in Figure 10, the start-up pressure difference increases significantly with the increase of water

saturation, and the smaller the permeability, the more significant the start-up pressure difference which is affected by water saturation.

Tight reservoir pore structure is complex, and the reservoir rock is hydrophilic. When there is formation water in the reservoir, water is first distributed on the surface of rock as a thin film, and the throat radius is small, it is easily enclosed by the formation water, therefore, the distribution of gas and water in the reservoir is discontinuous. In the process of development, the capillary resistance generated by the water cut off bubbles is superimposed and the value is huge, resulting in serious block to the fluid seepage.

3.3. The relationship between starting pressure and formation pressure

In order to further evaluate the relationship between starting pressure and overburden pressure, through physical simulation test of step-down internal pressure, the starting pressure gradient under different physical properties and different effective stress was determined. The experiment selected natural cores with the permeability 0.1mD and 0.8mD respectively, and saturated the average water saturation of Sulige gas field 50%. The core that meets the water saturation requirement is loaded into a high pressure gripper, and the confining pressure is increased to 35MPa. Then the saturated gas is pressurized from both ends of the core at the same time, till the pressure at both ends reaches 30MPa. Using the automatic control backpressure system, and gas step-down developed from the outlet end, meanwhile recorded the pressure at both ends of the core, the gas flow, water flow and pressure at the outlet. When no gas is produced at the experimental outlet, the pressure difference at both ends of the experimental core is recorded as the starting pressure difference. Descending step by step until outlet reaches the abandoned formation pressure 2.0MPa.

The test results show that, as shown in Figure 11, the starting pressure difference increases with the increase of effective stress, and the two have an exponential relationship. With the increase of effective stress, the starting pressure difference of the core with good physical properties increased slightly, while the starting pressure difference of the core with poor physical properties increased significantly with the increase of effective stress.

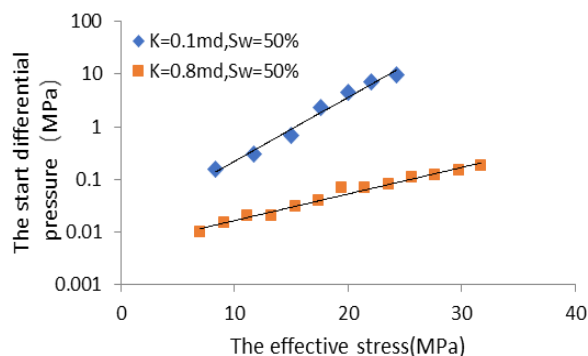


Figure 11. The effective stress and start differential pressure diagram.

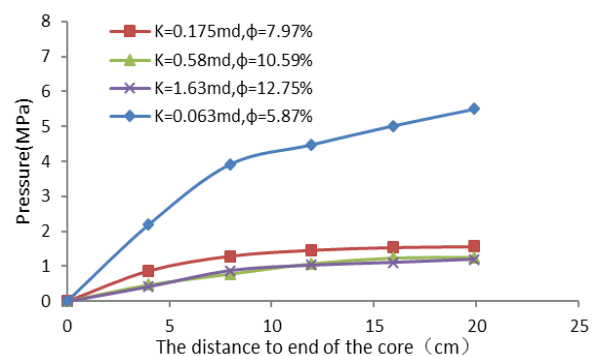


Figure 12. Pressure profile of different physical reservoirs with water saturation of about 50%.

The effective stress is the difference between overburden pressure and formation pressure, and the gas reservoir development process is actually the process of formation pressure reduction, that is, the process of effective stress increase. In the process, reservoir pore and throat become smaller because of the effective stress increase, especially throat radius decrease, and also water film thickness increases caused by formation pressure decrease. Both changes will further increase the flow resistance of gas and water and increase the starting pressure.

As shown in Figure 12, in the different physical and same water saturation (about 50%) reservoirs depletion development experiment, the closer to the end of the composite core, the greater the pressure difference. The worse the reservoir property is, the greater the pressure difference become. This

indicates that the pressure gradient of tight gas reservoir is not constant from the bottom of the well to the periphery. As the distance increases, the effective stress decreases and the starting pressure decreases. It is shown that there is an obvious pressure drop funnel in the near well zone, and the pressure change in unit length is large, while the pressure change in unit length in the far well zone is small. According to the analysis, the starting pressure difference of tight gas reservoir is significantly affected by effective stress, which leads to the existence of pressure drop funnel in gas well, therefore it determines the pressure range and affects the recovery rate of gas reservoir.

Based on the above factors, the reservoir starting pressure gradient is affected by reservoir pore structure (mainly for the throat radius), fluid properties (water saturation, this experiment did not consider the effect of viscosity, components, etc), pressure environment (such as formation pressure and effective stress) of the reservoir.

4. Revelation

The upper palaeozoic sandstone reservoir in Sulige gas field has the characteristics of dense reservoir, high water saturation and low pressure. And the effective permeability is very small, as a result, gas well production is low, and there is a large starting pressure gradient in the production process, especially near wellbore area, the reservoir pressure decreases, the start-up pressure increases, the peripheral supply is insufficient, so the output decreases rapidly. Meanwhile, due to the large start-up pressure and small pressure spread range, the controlled dynamic reserves of gas well are low, so the cumulative gas production and recovery rate are low.

Based on the experimental conclusion, the following aspects should be done well in the development of tight sandstone gas reservoir:

(1) Well location optimization, it is necessary to ensure the well location deployed in the reservoir with good physical property and high gas saturation, which is beneficial to reduce the starting pressure of gas reservoir. More importantly, it also can reduce the starting pressure of the near well zone caused by the increase of effective stress and water invasion.

(2) Optimize perforation, and avoiding water producing layer as much as possible. Some of the multilayer produce water and the bottom of the well accumulates liquid, which can increase the water saturation and the starting pressure near well reservoir.

(3) Improving the fracturing effect and recovery rate of fracturing fluid. With the gas well entering the middle and late development period, the effective stress in the near well zone increases, and the starting pressure will increase significantly. If the fracturing fracture length can be effectively increased through reservoir reconstruction and the conductivity of the proppant can be improved, the start-up pressure gradient can be reduced, the gas well pressure can be extended and the production can be increased. In particular, the proppant with better long-term flow conductivity can be optimized, which has obvious effect on the normal production of gas well in the later period. For tight sandstone gas reservoirs, it is very important to flow fluid back timely after fracturing reconstruction and reduce fracturing fluid pollution in reservoirs near wells.

(4) Timely and effective drainage gas recovery measures should be taken. Because the reservoir water saturation is high, there exists a certain degree of water production in the middle and late period of gas well production. For low-yielding gas wells, timely and effective drainage can help reduce the bottom hole fluid accumulation, reduce the water invasion damage near the well area, and improve the gas reservoir development effect.

5. Conclusions

(1) Compared with low-permeability reservoirs, tight reservoirs have small throat radius, and the proportion of pore volume controlled by micro throat is large, the throat is not only a seepage channel but also an important storage space.

(2) Throat radius, water saturation and effective stress are the most important factors to determine the starting pressure difference of reservoir.

(3) Optimization well location, optimization perforation, upgrading fracturing reformation effect, improving fracturing fluid flowback rate, timely and effective drainage gas recovery measures should be taken to reduce the start-up pressure near wellbore area, to improve the effect of gas well development.

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