Evaluation of horizontal well productivity in the abnormal high pressure and low permeability gas reservoir in the west of the South China Sea

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Abstract. Based on the actual geological reservoir characteristics of an abnormally high-pressure gas reservoir in the western South China Sea, and considering reservoir stress sensitivity, a single-well model for horizontal wells was established to study the law of non-steady-state productivity of horizontal wells. Based on the established single well model of horizontal wells, and considering stress-sensitive conditions, the rational allocation of single wells is studied. The research results show that the initial unobstructed flow rate of the horizontal well is high and it decreases rapidly; the non-resistance flow considering stress sensitivity is lower than the non-resistance flow without considering stress sensitivity. The difference between the two gradually reaches the maximum at the beginning of the well, and the difference gradually decreases at the later stage; there are interrelationships and constraints between single good production, stable production time, and final production.

Key words: Abnormally high-pressure gas reservoir, horizontal well, stress sensitivity, productivity evaluation.

1. Introduction
Deep oil and gas reservoir exploration and development has received special attention. These reservoirs often show high pressure, such as Keshen-1, Xinjiang, well depth 6388 m, formation pressure equivalent density greater than 2.0g/cm3, formation temperature 142°C; western South China Sea Oil company Y21-1-3, with a well depth of nearly 5,000m, formation pressure equivalent density greater than 2.0g/cm3, and formation temperature above 200°C; Yingke-1 in Xinjiang, Lengke-1 in Qinghai, Wells such as Victory Hao Ke-1 experienced similar conditions of high temperature or high pressure. The characteristics of abnormally high-pressure gas reservoirs are different from those of atmospheric pressure gas reservoirs. Therefore, during the development of gas fields, there are many differences between abnormal high-pressure gas reservoirs and atmospheric pressure gas reservoirs. It is mainly manifested in the following five aspects: the driving force source is large and the energy is large; during the development process, the reservoir has obvious deformation; the pressure system segmentation may occur during the low-pressure gas production period of the gas reservoir; the abnormally high-pressure gas reservoir and atmospheric pressure gas reservoir The pressure drop curves are different; the productivity of abnormally high-pressure gas reservoirs is affected by stress sensitivity. Reservoir stress
sensitivity refers to the phenomenon that the permeability of oil and gas layers changes with the change of effective stress. The so-called effective stress is usually defined as the difference between the overburden pressure and the fluid pressure. As the development progresses, the pore pressure gradually decreases, resulting in changes in the effective stress of the rock, which leads to changes in the physical parameters (porosity, permeability, and compression coefficient) of the reservoir. The nature of the reservoir that changes with effective stress is called the stress sensitivity of the reservoir. During the production of abnormal high-pressure gas reservoirs, as the gas is produced, the formation pressure is continuously reduced, and the effective stresses on the reservoir rocks are greatly increased, causing significant deformation of the reservoir rocks, which leads to a decrease in reservoir permeability and further affects Gas well productivity. Stress-sensitive effects are common in abnormal high-pressure gas reservoirs; stress-sensitive effects must be considered in reserve calculations, single-well productivity calculations, well test analysis and numerical simulation of abnormally high-pressure gas reservoirs; stress-sensitive damage is mainly determined by indoor evaluation and testing methods, and the internal pressure varies. Pressure and variable internal pressure and constant confining pressure are currently commonly used test methods. The variable internal pressure and constant confining pressure are consistent with the actual stress variation of gas reservoirs, and the test results are more representative. The development practice of abnormally high-pressure gas reservoirs and the development of gas wells show that the impact of reservoir stress sensitivity on production cannot be ignored. With increased sensitivity, production capacity is significantly reduced. Under different conditions, gas well productivity decreases to varying degrees [1]-[11].

An abnormally high-temperature and high-pressure gas reservoir in the western South China Sea is mainly a gas reservoir controlled by structure and lithology. It can be divided into multiple wells on the plane. Each well is an independent gas-water system. There are many structures and lithologic gas reservoirs with different sets of gas-water systems. From the perspective of gas-water distribution, each gas layer is mainly distributed in higher parts of the structure, with different gas-water interfaces and pressure systems. The original formation pressure is relatively large, and the pressure coefficients of most blocks are 1.9-2.0. Around 2.3, the formation temperature is high (ground temperature gradient 4.1°C/100m), and the main gas group has a large gas-bearing height. The main driving types are edge water driving and elastic flooding. The porosity of the reservoir section is 15.0% -23.0%, and the permeability is 0.11mD-23.27mD. It is a mesoporous and low-permeability reservoir.

2. Model building
The size of the single well model of the established horizontal well is 2500m×2000m×15m, the depth of the central reservoir is 2825m, the thickness of the reservoir is 15m, the original formation pressure is 53.43MPa, the porosity is 18.8%, and the initial gas saturation is 69.3%. In order to study the production capacity under different permeability, four cases of horizontal permeability 2.5mD, 5mD, 10mD, and 20mD were simulated, and the vertical permeability was 0.1 times the horizontal permeability. The block center grid is selected, the grid step size is 20m×20m×1m, and the total number of grids is 125×100×15=187500. The horizontal section of the horizontal well is located in the middle of the gas reservoir on the plane. The good trajectory is along the long axis of the model, and it is 3 m from the top surface in the longitudinal direction. The original geological reserves of the horizontal well single well model are 29.90×108m3.

The relative density of natural gas is 0.757, and the change in volume coefficient and viscosity of natural gas with pressure is shown in Figure 1; This model considers gas-water two-phase infiltration. The existing two groups of different infiltration curves are phase infiltration 1 and phase infiltration 2 respectively, and the differences between the two are quite large, as shown in Figure 2.
In order to correctly select the permeability curves, the two well permeability models were used to test the two permeability curves separately and compared with the on-site productivity test results. The comparison results are shown in Table 1. The calculation result of phase infiltration 2 is obviously small. After comprehensive consideration, this model uses infiltration 1.

### Table 1. Comparison of calculation results of different phase permeability curves with field test results

| Name                  | Formation permeability (mD) | Effective thickness (m) | Gas production index ($10^4$ m$^3$/d·MPa) | Gas recovery index ($10^4$ m$^3$/d·MPa·m) | Remark                          |
|-----------------------|-----------------------------|-------------------------|-------------------------------------------|--------------------------------------------|---------------------------------|
| Relative permeability 1 | 10                          | 20                      | 11.5-14.5                                 | 0.58-0.73                                  | Inclined shaft, well angle 56.3 ° |
| Relative permeability 2 | 10                          | 20                      | 0.8-1.4                                   | 0.04-0.07                                  | Inclined shaft, well angle 56.3 ° |
| testing on the spot   | 8.3                         | 8.2                     | 4.5-5.4                                   | 0.55-0.66                                  | —                               |

3. Stress-sensitive parameter settings

The stress-sensitive parameters are set in the model, and the parameters are multiples of pore volume and conductivity change under different pore pressures. Since the apparent volume of the grid block is unchanged, the multiple of the pore volume with pressure is equal to the multiple of the porosity with pressure. The definition of the block center grid conductivity (taking the X direction as an example) is:

$$TRANX_i = \frac{CDARCY \cdot TMLTX_i \cdot A \cdot DLPC}{2} = \frac{\frac{DX_i}{PERMX_i} + \frac{DX_j}{PERMX_j}}{B}$$

In the formula, CDARCY is Darcy's constant; TMLTXi is the multiple of conductivity; A is the interface area of grid I and grid j; DLPC is a parameter reflecting the inclination of the stratum; Length in the direction; PERMXi, PERMXj are the permeability of grid I and grid j in the X direction, respectively. The stress-sensitive experimental data were averaged, and the values under the original formation pressure were taken as reference values (multiplication factor is 1) to obtain the pore volume and conductivity multiplied by pressure, as shown in Figure 3.
Figure 3. Variation of pore volume multiple and conductivity multiple with pressure

4. Simulation calculation
Based on the established single well model of horizontal wells, by setting the downhole flow pressure to atmospheric pressure (0.1 MPa), the change of unobstructed flow with time and formation pressure was calculated. In order to reflect the effect of stress sensitivity on gas well productivity, a comparison of unobstructed flow with and without stress sensitivity is made. The calculation results are shown in Figure 4-Figure 11.

Figure 4. Variation of unobstructed flow over time (K=2.5mD)

Figure 5. Variation of unobstructed flow with formation pressure (K=2.5mD)

Figure 6. Variation of unobstructed flow over time (K=5mD)

Figure 7. Variation of unobstructed flow with formation pressure (K=5mD)
It can be seen from Figs. 4–9 that the initial unobstructed flow rate of the horizontal well is high at the beginning, and the unobstructed flow rate decreases rapidly in the initial stage, and the unobstructed flow rate decline gradually in the middle and late stages. The unobstructed flow decreases with the formation pressure. When the formation pressure is higher than 50MPa, the unobstructed flow decreases rapidly and is approximately straight. When the formation pressure is lower than 50MPa, the unobstructed flow decreases gradually. The unimpeded flow considering stress sensitivity is lower than the unimpeded flow without stress sensitivity. The difference between the two gradually reaches the maximum at the beginning of the well opening, but both do not exceed 4% of the unobstructed flow during the same period. With the formation of energy exhaustion in the later period, the formation pressure gradually As a key factor in controlling the productivity of gas wells, the difference between considering and not considering stress-sensitive unobstructed flow gradually decreases. The lower the permeability, the greater the stress sensitivity and the more significant the effect.

5. Research on rational allocation
Based on the established single well model of horizontal wells, and considering stress-sensitive conditions, the rational allocation of single wells is studied. Taking into account the three cases of horizontal permeability of 2.5mD, 5mD, 10mD, the evaluation period is 20 years, the wellhead waste pressure is 3.5MPa. The forecast of production dynamic index and analysis of reasonable allocation are shown in Figures 10-12.

Figure 8. Variation of unobstructed flow over time (K=10mD)

Figure 9. Variation of unobstructed flow with formation pressure (K=10mD)

Figure 10. Analysis of the rational distribution of single wells in horizontal wells (horizontal permeability 2.5mD)
Figure 11. Analysis of the rational distribution of single wells in horizontal wells (horizontal permeability 5mD)

Figure 12. Analysis of the rational distribution of single wells in horizontal wells (horizontal permeability 10mD)

As can be seen from Figures 10 to 12, due to the interrelationships and constraints between single-well production, stable production time, and final production, a reasonable production allocation plan should ensure a certain single-well production, relatively long stable production time and higher final recovery. After comprehensive consideration, the horizontal wells with the recommended horizontal permeability of 2.5mD, 5mD, 10mD, and 20mD, respectively, are distributed at 60×10⁴m³/d, 80×10⁴m³/d, 100×10⁴m³/d, and 120×10⁴m³/d the left and right are more reasonable.

6. In Conclusion

(1) Considering the reservoir stress sensitivity, a single-well model for horizontal wells was established. Combined with stress sensitivity experiments, the law of the unsteady productivity of horizontal wells was studied.

(2) The unobstructed flow decreases with the increase of well opening time. The initial unobstructed flow is high at the beginning of the well, and it decreases rapidly, and then the decline gradually slows down. The unobstructed flow decreases as the formation pressure decreases. When the formation pressure is higher than 50 MPa, the unblocked flow rate decreases rapidly, which is approximately straight; when the formation pressure is lower than 50 MPa, the unblocked flow rate decreases gradually.

(3) In the early stage of well opening, the effect of stress sensitivity on unobstructed flow cannot be ignored; in the latter stages of production, the effect of stress sensitivity on unobstructed flow is small and can be ignored.

(4) Based on the established single well model of horizontal wells, and considering stress-sensitive conditions, a rational allocation study of single wells was carried out, and horizontal well single well allocations under different physical properties were recommended.
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