Research on optimization design method of horizontal well of volcanic gas reservoir in Daqing Xushen deep natural gas field

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Abstract: The volcanic gas reservoir in Daqing Xushen deep natural gas field has low porosity, low permeability, strong heterogeneity, more bottom water layer, low production of vertical wells in most blocks and other characteristics. The development of horizontal well can better improve the development effect of gas reservoir. The optimization design method of “One choice, two determination and three optimization” horizontal well is established based on the gas reservoir geology and dynamic new achievements on the fine identification of volcanic bodies, prediction of well control range of gas wells and so on according to the characteristics of volcanic bodies controlling reservoir development. This method shall be applied to the optimization design of horizontal wells, which makes the production capacity of the well increase significantly and better ensures the continuous and stable exploitation of gas reservoir.

1. Introduction
The explored gas bearing area of volcanic gas reservoir in Daqing Xushen deep natural gas field is 327.34km², and the submitted geological reserves of explored deep gas is 2457×10⁸m³. This deep natural gas field was developed in 2004 with the increasing year by year output, and the annual gas output in 2019 is nearly 20 × 10⁸m³. The comprehensive analysis of gas field development status: Firstly, the undeveloped reserves account for a large proportion and well control degree and reserve utilization degree of part zones are low; Secondly, volcanic body controls reservoir distribution and reservoir development and productivity difference between blocks is large; Thirdly, vertical wells generally have low production and rapid decline, and most the production of horizontal wells in most blocks is much higher than that of vertical wells. It is not difficult to see that the development of horizontal well is one of the main methods of current and future volcanic gas reservoir in this deep natural gas field to speed up production capacity construction and enhance well control dynamic reserves. Therefore, research on optimization design method of horizontal well based on gas reservoir geology and dynamic cognition has been developed so that better optimization of horizontal well trajectory is used to enhance the drilling catching rate and production capacity of horizontal well reservoir so as to enhance the development effect of gas reservoir.

2. Latest understanding of relevant geology and dynamics on volcanic gas reservoir in researched gas field

2.1. Finely depict and recognize the volcanic bodies according to the different eruption period
There are three periods of eruption in the interior of the target layer of this volcanic gas reservoir. Adopt the associative method of “plane, section and three-dimensional space” depiction and
take the single well facies as constraint and volcanic body type and seismic response model as guidance to finely depict and recognize the each volcanic body according to the different eruption period. The Figure 1 is the seismic profile depicted according to the volcanic body of volcanic reservoir in a block and there are 25 volcanic bodies distinguished through three eruption period in this block, which overlap each other in the longitudinal direction and cross each other in the plane.

![Seismic profile](image)

**Figure 1.** The seismic profile depicted according to the volcanic body in a block

### 2.2. Distribution characteristics of gas and water of volcanic gas reservoir in researched gas field

Table 1 is the latest division result table of gas-water interface of single well in a block and the ground elevation of its gas-water interface is from -3610 to -3830m. It can be seen that the distribution of gas and water is particularly complex. There are the following characteristics:

- Follow the regular pattern of gravity separation and the distribution characteristic in general is that water is under the gas. The gas layer is mainly distributed in the upper part of the third eruption period, and the water layer is mainly distributed in the second and first eruption periods.
- On the macro level, gas-water interface of the adjacent wells may exist large differences with controlled by structure and volcanic body.
- On the micro level, the capillary force of reservoir is the main resistance of the filling of nature gas, which not only influences differential filling of natural gas and even restricts the difference of gas water content in the gas reservoir after the formation of reservoir leading to different gas-water interfaces in one volcanic body.

| Well number | Surface elevation | Bushing altitude | Altitude depth of gas-water interface |
|-------------|------------------|------------------|-------------------------------------|
| Well 1      | 169.9m           | 180.4m           | -3800m                              |
| Well 2      | 169.3m           | 179.8m           | -3810m                              |
| Well 3      | 185.6m           | 190.5m           | -3690m                              |
| Well 4      | 180.0m           | 185.5m           | -3610m                              |
| Well 5      | 173.3m           | 182.3m           | -3830m                              |
| Well 6      | 180.0m           | 187.5m           | -3750m                              |

### 2.3. Prediction of gas well control range of volcanic gas reservoir in researched gas field

The combination method of numerical simulation and well test is used to predict the well control range here. Firstly, we must establish the fine numerical model of gas reservoir and carry out simulation of formation pressure change of gas reservoir. Then, we use the dynamic analysis of modern production to calculate single well controlled dynamic reserves and supply radius. Finally, the well control range of each single well has been predicted to lay the foundation for optimization design of horizontal well location according to numerical simulation of pressure change process and calculation results of supply radius.
3. Optimization design method of horizontal well in researched gas field

The optimization design method that "one selection, two determination and three optimization" for horizontal well is established and will be described in detail below according to the characteristics that volcanic body controls reservoir layer development with strong heterogeneity and relatively more bottom water layer of volcanic gas reservoir in this gas field.

3.1. Select volcanic body
Select volcanic bodies that meet the following conditions to carry out the design of horizontal well:
- Select the volcanic bodies with development potential that the remaining geological reserves of volcanic body is at least more than economic limit of well control geological reserves of horizontal well (about $5 \times 10^8 m^3$) according to the calculation results of geological reserves of volcanic body and gas well controlled dynamic reserves in the body.
- Select the volcanic body with thick effective reservoir within gas bearing area according to effective reservoir prediction results of volcanic gas reservoir.
- Select volcanic bodies with high production and good physical properties according to the existing wells in the volcanic body.

3.2. Determine development mode and well layout method

3.2.1. Determine development mode
According to the distribution range of the selected volcanic body, geological reserves and development potential, it can be divided into three development mode: "Single-well single-body" mode, "Single-well multi-body" mode and “Multi-well single-body” mode. If the geological reserves of volcanic body or gas bearing area can only support one horizontal well to be developed, "Single-well single-body" mode can be used to develop. If the geological reserves and distribution range of volcanic body is small which cannot reach the economic limit, "Single-well multi-body” mode can be used to develop. If the volcanic body is large in scale, relatively good in physical properties and large residual area, “Multi-well single-body” mode can be used to develop.

3.2.2. Determine well layout method
According to the cognition level and well control degree of the selected volcanic body, it can be divided into three kinds of horizontal well arrangement: "Pilot vertical well and sidetrack horizontal well", "Branch horizontal well" and “Conventional horizontal well". If volcanic body is a newly discovered or recognized one without other reference gas well in the body, it is believed that this kind of volcanic body is poorly recognized so it is suggested to design a guide well with vertical well pattern to determine gas bearing property, gas and depth of water layer, and then sidetrack horizontal well according to the actual situation of guide well, which will greatly reduce design risk. If the well control degree of volcanic body is low and the remaining area is large, it is suggested to design “Branch horizontal well” for gas reservoir development so as to reduce drilling cost and improve economic benefit. If the understanding and well control of volcanic bodies are relatively high, “Conventional horizontal well” is used to develop.

3.3. Optimize the direction, location and length of horizontal wells

3.3.1. Optimize the direction of horizontal well
Physical property of volcanic gas reservoir in this gas field is bad in general and the existing gas wells all need fracturing transformation to be able to maintain long-term stable production. Therefore, The direction of formation principal stress should be fully considered in the design of horizontal well direction. The directions of principal stress of volcanic gas reservoir in Xushen natural gas field are all near east-west, so the optimized design direction of horizontal well is north-south or near north-south so as to try best to enhance the fracturing effect and improve productivity.
3.3.2. Optimize the horizontal section location of horizontal well

Plane position optimization: The difference of well control range of volcanic gas reservoir in this gas field is larger, so it cannot use the fixed well spacing, and determine well spacing according to the supplied radius of adjacent wells. The calculation result of well spacing is 500~800m in general according to the experience and single well supply radius. In the uncontrolled area of gas wells on volcanic bodies with development potential, select high location, large effective thickness of reservoir, location of seismic characteristics similar to adjacent high production wells to optimize the horizontal well plane position.

Longitudinal position optimization: The gas layer is mainly located at the top of volcanic rock due to the regular pattern of gravity separation, so the horizontal section of the well should be as close to the top of the reservoir as far as possible. At the same time, because the gas reservoir bottom has water layer in general, the horizontal section of the well must be at a certain distance from the gas-water interface so as to prevent the premature bottom formation water coning and prolong the gas recovery period without water as far as possible.

3.3.3. Optimize the length of horizontal well

Optimize the length of horizontal well according to the following several principles:

- The lowest point of horizontal well should keep at least more than 50m from the gas-water interface according to the past experience.
- Ensure that the effective thickness of the horizontal section is not less than the economic limit (Generally 10m).
- We should increase horizontal section length as much as possible to increase capacity.

4. Application effect of optimization design method of horizontal well

There are 10 horizontal wells are designed in the volcanic gas reservoir of this gas field in total by using this method. At present, three horizontal wells have been completed. Their effective reservoir layer catching rate of horizontal section is 62~96% and open flow of test gas is 22.2~103×10^8 m^3/d that is 1.3-1.6 times of the adjacent horizontal wells and they do not produce the formation water. In this way, the productivity of horizontal wells is significantly improved with good application effect(Table 2 is the application effect statistics table). This method provides strong support for the improvement of the degree of gas reservoir production and the capacity support.

| Horizontal well number | Effective reservoir layer catching rate | Open flow of test gas | Open flow of design well gas test/Open flow of gas test in adjacent horizontal wells |
|------------------------|----------------------------------------|----------------------|--------------------------------------------------------------------------------------|
| Horizontal well 1      | 96%                                    | 103×10^8 m^3/d       | 1.6                                                                                  |
| Horizontal well 2      | 69%                                    | 73×10^8 m^3/d        | No adjacent horizontal well                                                              |
| Horizontal well 3      | 62%                                    | 22×10^8 m^3/d        | 1.3                                                                                  |

5. Conclusions

Based on the above discussion, the summary is as follows:

(1) The volcanic gas reservoir consists of many volcanic bodies in Daqing Xushen deep natural gas field. The relationship between gas and water is very complex. The difference of well control range is large.

(2) The flow of the optimization design new method of horizontal well is: selecting volcanic body; determining development mode and well layout method; optimizing the direction, location and length of horizontal wells.

(3) By this method the productivity of horizontal wells is significantly improved. The optimization design method is of great significance to promote.
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