Optimization and utilization of peak-shaving capability for water drive gas storage

Yangyang Bi¹, Tuanhui Liu¹³, Zengqiang Xi¹, Wenfeng Huang² and Qing Xia¹

¹Exploration and Development Research institute of HuaBei Oilfield Company; ²The Fifth Exploit of HuaBei Oilfield Company

Abstract. To determine the reasonable gas injection and production quantity and to minimize the influence of water invasion on the operation of underground gas storage is one of the key factors to decide whether the water drive gas storage can fully exert its peak shaving ability. At present, gas reservoir engineering method is mainly used in China, which mainly reflects the operation of underground gas storage under the condition of less water invasion at the end of gas production, it cannot really reflect the influence of water invasion on the operation of underground gas storage under the condition of large injection-production volume. Through the numerical simulation and the research of the injection-production performance, it is clear that the main geological factors affecting the reasonable injection-production rate of the gas storage are the pressure of the gas storage, the properties of the reservoir, the distribution of gas and water and the radius of well control. Based on the reservoir changes of pressure, water yield, gas-water ratio, gas-water interface and saturation, and according to the influence of multi-period water invasion on the operation of gas storage, the optimization technology of peak shaving capacity of water drive gas reservoir is established, which successfully guides the optimization of injection-production operation of an underground gas storage in China. The result shows that after 5 cycles of operation, the gas injection displacement effect is successful, the gas production capacity is improved gradually, and the peak shaving capacity is $6.85 \times 10^8$ m$^3$ in 2019. The conclusion is that the optimization technology of peak shaving capacity is applicable to some extent, which provides theoretical basis and operating experience for the design of injection-production operation of the same type gas storage in China.

1. Introduction
Underground gas storage that rebuilt upon the developed gas reservoirs are the most important type of underground gas storage [1-2] in China at present. But most gas reservoirs generally have edge and bottom water [3]. To determine the reasonable gas injection and production quantity and to minimize the influence of water invasion on the operation of underground gas storage is one of the key factors to decide whether this kind of gas storage can give full play to its peak shaving ability. Therefore, the main factors that affect the reasonable allocation of production and injection can be determined by numerical simulation and the study of injection-production performance [4]. Based on the changes of gas reservoir pressure, water yield, gas-water ratio, gas-water interface and gas saturation, combined with operation test, the peak regulation capacity of water drive gas reservoir can be optimized.
2. Geological characteristics
The structure of a gas storage is high in the East and low in the west, with a buried depth of 4400m. The gas reservoirs are located in Fengfeng formation and Shangmajiagou formation of Ordovician. The reservoir has poor physical properties, low porosity and permeability. At the end of exploitation, some gas wells are affected by bottom water. The original pressure was 47.9 MPa, and after more than 20 years of exhausted gas production, the formation pressure is now 29.9 MPa (before the reservoir is built). Eclipse double medium component model was used to predict the water invasion along fractures and the influence of bottom water invasion on the operation of underground gas storage.

3. Analysis of influencing factors
The influencing factors of peaking capacity of gas storage in operation are mainly related to the injection-production dynamic characteristics and internal operation mechanism of water drive gas storage [5]. The simulation experiment of gas and water mutual drive found that after a long-term injection and production operation, the water phase seepage capacity will be enhanced. Therefore, more active edge water migration can result in a large number of residual gas and bound water in the pore space of the reservoir [6], which will directly reduce the peak capacity of the gas storage. This paper summarizes the factors that affect the peak shaving ability of water drive gas storage in its periodic operation.

First, most of the water drive gas reservoirs in China are rebuilt from the gas reservoirs developed to the last stage or exhausted, so the reservoir pressure is low and the gas-water interface is much higher than the original gas-water interface. When gas is injected into a gas storage, excessive gas injection in a certain area will lead to uneven reservoir pressure and uneven gas-water interface migration, and too much gas injection in a single well will lead to gas channeling or gas-water interlock, all these will affect the gas drive sweep efficiency of the gas storage. Therefore, we should optimize the single well gas injection rate to keep the reservoir pressure balance, so as to improve the utilization ratio of gas storage and give full play to its peak-shaving capacity.

Second, during the high-speed injection-production process of water drive gas reservoir, the pressure changes in the reservoir with edge and bottom water flowing back and forth. During gas production, the pressure in the reservoir decreases, which leads to the elastic expansion of natural gas, rock particles and formation water, and the re-compaction of surrounding rocks, which leads to water invasion. With the increase or decrease of injection-production process, the gas-water interface also increases or decreases. Formation Water Migration will determine the width of pure gas zone and transition zone of gas-water drive [7], which directly affects the efficiency of reservoir space utilization (Figure 1).
Lastly, the multi-period operation of gas storage makes the properties of near-well reservoir change complicatedly, so the peak shaving gas quantity of underground gas storage may not be equal to the recoverable reserves of original gas reservoir. Therefore, the multi-period reservoir capacity review should focus on the determination of gas pore volume, gas swept volume and available pore volume [8].

4. Operation analysis of gas storage

4.1. Gas injection analysis
The gas storage has been injected since 2014. According to the structure of the gas storage and the construction of the project, the upper part of the middle-east structure and the top of the gas storage have been injected preferentially, and the capacity has been expanded gradually. During the 2014-2015 cycle, the gas was injected into the upper part of the structure with a total of $1.7\times10^8$ m$^3$, the pressure at the end of gas injection was 33 MPa in the northern part of the reservoir, and 28 MPa in the non-gas injection area in the southern part, and the gas-water transition zone in the northern part gradually moved down. During the 2015-2016 cycle, three wells in the central part of the structure began to inject gas into the reservoir step by step, with a total gas injection of $2.8\times10^8$ m$^3$. The pressure at the end of gas injection in the northern part of the reservoir was 38 MPa, and that in the southern part was 33 MPa. The gas-water transition zone in the middle of the structure moves down obviously, and the usable inventory of the gas reservoir increases. During the 2016-2017 cycle, all the wells begin to inject gas into the reservoir, with a total gas injection of $4.7\times10^8$ m$^3$. After all the wells are put into use, the gas storage has entered into a smooth gas injection operation, and reasonable coordination among the gas injection wells has been carried out. By 2019, the designed storage capacity of the gas storage at the end of gas injection has been achieved, the reservoir pressure is 45 MPa, and the gas-water interface moves down evenly during gas injection.

In the early stage of gas injection, the gas injection priority in the north of the gas reservoir leads to high pressure in the north and low in the south, and the gas water interface is low in the north and high in the south, so the production wells in the South cannot be put into operation. Through multi period optimization of gas injection and production, the pressure of gas storage is gradually balanced, the gas water interface is relatively stable, and the single well productivity of all injection and production wells is improved. Therefore, reservoir pressure and gas water interface distribution are one of the main geological factors that affect the reasonable injection-production rate of gas storage.

4.2. Gas production analysis
The gas storage was reconstructed from medium water drive gas reservoir. It is easy to be affected by water invasion and water flooded, resulting in limited gas production by injection and water carrying in peak shaving gas production [9]. Based on the numerical simulation and the research of injection-production dynamic tracking, the peak regulation capacity of gas storage is optimized. According to the effective thickness, reservoir characteristics and percolation ability, the gas producing wells are divided into 3 types. Based on well test and productivity equation calculation, it is determined that the reasonable gas production capacity of type I well is $50\times10^4$ m$^3$/d, type II well is $40\times10^4$ m$^3$/d, and type III well is $30\times10^4$ m$^3$/d. The productivity of single well is better in the middle-north and high position, and worse in the south and low position. The peak shaving capacity of the gas storage is gradually enhanced, and reaches $6.85\times10^8$ m$^3$ in 2019. The gas-water transition zone in the well area with large gas production fluctuates greatly at the end of gas production period. The water production and water-gas ratio of the gas storage are low, and the gas-water ratio is controlled at about 0.1 m$^3$ / $10^4$ m$^3$, which ensures that the gas storage is less affected by edge and bottom water.

Through the comparison of single well productivity calculation results show that the productivity of single well is related to the distribution of reservoir physical properties. The area with good reservoir physical properties has better single well productivity [10]. Therefore, the properties of the
reservoir are one of the main geological factors that affect the reasonable injection-production rate of gas storage.

4.3. The multi-cycle working inventory of gas storage

The gas in a water drive gas reservoir is mainly driven by drilling holes, during the injection-production process after the establishment of the reservoir, it is difficult for the gas phase to displace the micro-channels, which leads to the decrease of effective well control radius and the low control degree of well pattern, so that part of the gas storage space can’t be used (Figure 2). According to this situation, the concept of available inventory is put forward, which is used to express the available inventory [11].

![Figure 2. Relation diagram of calculation parameters of gas storage capacity.](image)

**Table 1. Calculation table of gas storage capacity.**

| Cycle | Static inventory ($10^8$m³) | Available inventory ($10^8$m³) | Available pore volume ($10^8$m³) | Operational gas ($10^8$m³) | Cushion gas ($10^8$m³) | Storage capacity ($10^8$m³) |
|-------|-----------------------------|-------------------------------|----------------------------------|-----------------------------|------------------------|-----------------------------|
| 15-16 | 26.64                       | 6                             | 0.03                             | 2.95                        | 25.33                  | 28.28                       |
| 16-17 | 30.82                       | 12.5                          | 0.04                             | 3.92                        | 28.17                  | 32.09                       |
| 17-18 | 33.61                       | 16.5                          | 0.06                             | 5.41                        | 29.36                  | 34.77                       |
| 18-19 | 34.54                       | 19.3                          | 0.07                             | 6.21                        | 29.45                  | 35.66                       |

Firstly, the available inventory is calculated by RTA software. Secondly, the available pore volume is obtained by converting the available inventory to underground [12]. Finally, the inventory under different pressure can be calculated by converting the available pore volume to different pressures (Table 1).

The calculations show that when the injection-production pattern is perfect and the injection-production method is reasonable, the available inventory increases, which leads to the increase of the available degree of the gas storage [13]. Therefore, the radius of well control is one of the main geological factors that affect the reasonable injection-production rate of gas storage.

5. Conclusions

First, the main geological factors affecting the reasonable injection-production rate are the pressure of the gas storage, the properties of the reservoir, the distribution of gas and water and the radius of well control.

Second, based on the changes of reservoir pressure, water yield, gas-water ratio, gas-water interface and saturation, and according to the influence of multi-water invasion on the operation of gas storage, the peak-shaving gas quantity of gas storage can be optimized.
Lastly, the optimization technology has been applied to a gas storage for 5 cycles, the gas injection displacement effect is successful, the gas production capacity is improved gradually, and the peak shaving capacity is $6.85 \times 10^8$ m$^3$ in 2019.

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