Study on reasonable gas recovery rate and adjustment scheme of bottom water gas reservoir

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Abstract: During the exploitation of bottom water gas reservoirs, the gas wells have a serious impact on the development of gas reservoirs. Based on the systematic analysis of the production dynamics and water intrusion characteristics of the bottom water gas reservoir in the XS gas field, combined with seismic, geological, well logging, production testing and other data, a numerical simulation model was established to demonstrate the rational gas production rate after gas reservoir seeing water. Research on the mechanism of water control. The gas reservoir numerical simulation technology is used to determine the reasonable gas production speed of the gas well, which can alleviate the bottom water coning rate and prolong the waterless gas production period. Combined with measures such as drainage, water shutoff, and shut-in, the rational gas production rate and adjustment measures for the bottom water gas reservoir are formulated.

1. Introduction
In recent years, domestic and foreign scholars' research on the development of bottom-water gas reservoir mainly focuses on gas reservoir engineering and gas production technology, and they have conducted a lot of research on gas-water two-phase seepage mechanism, gas reservoir and well water production mechanism, water control measures and other aspects of bottom-water gas reservoir.

Christian¹ (1980) proposed the method of drainage and pressure reduction to improve the recovery rate of gas reservoirs. Trubaer et al. (1983) believed that water flooding gas field resulted in low recovery rate of gas field due to a large number of closed natural gas due to intrusive water. By draining the gas, when the reservoir pressure drops below the containment pressure, the containment gas reflows and is produced from the well. C. Balalf experiment of the former Soviet union shows that the recovery rate of gas reservoir is higher when the water flooded well is drained and the closed gas is produced, and the gas is produced at high speed without water flooded well. The theory of drainage gas recovery has been successfully studied in domestic and foreign gas field production practice, but there are still many problems in the efficient development of bottom water gas reservoir, which need to be further studied.

At present, numerical simulation technology plays an important role in evaluating the development effect of bottom water gas reservoir. Through the numerical simulation technology of gas reservoir, it is possible to study the water body energy and its activity rule, water invasion mechanism, gas well...
water production rule, reasonable exploitation speed and drainage gas production dynamic effect, etc. Typical edge and bottom water gas reservoirs have been successfully simulated in China, such as the development design of Wen23 fault block (sandstone bottom water gas reservoir)\cite{2-3} in Zhongyuan oilfield, the development evaluation of water invasion gas reservoir in Sichuan Dachigan\cite{4-5}, and the study on water control countermeasures of water invasion gas reservoir in Hebafei \cite{6-7}. This study mainly uses the gas reservoir numerical simulation technology to carry on the reasonable recovery velocity and the adjustment plan to the bottom water gas reservoir.

2. Gas reservoir overview
Block X2 of XS gas field is located in the north of Xujiaweizi fault depression of songliao basin. The gas reservoir is buried deep between 3200 ~ 3800m, the original formation pressure is 37.8MPa, and the geological reserves are $3.796.3 \times 10^8 m^3$. The X2 block of XS gas field was put into development in October 2009, with 23 production wells, 21 well openings and 7 Wells (3 shut-in wells). The cumulative gas production has reached $1374.26 \times 10^8 m^3$. In the early stage, the gas recovery speed is higher than the plan design, and the formation pressure drops rapidly. After the gas recovery speed is reduced, the formation pressure drops slowly and the development effect is improved, but the water invasion is not effectively controlled. Therefore, the research on reasonable gas recovery rate, gas reservoir and single well adjustment scheme is of great significance for the formulation of reasonable development technology policy\cite{8}.

3. Numerical simulation of bottom water gas reservoir

3.1. Establishment of fine geological model
Based on the structure, drilling, reservoir and logging, and considering the stress sensitivity of the abnormal high-pressure gas reservoir, the matrix model of block X2 of XS gas field is established. The faults and fractures near the well, the separation interlayer and the gas-water interface are mainly depicted, and the fault and fracture model in block X2 of XS gas field is established (figure 1). The PVT, phase permeability test, saturation test, gas-producing profile test and actual production data were fitted. The fitting geological reserves were $3803.4 \times 10^8 m^3$, the fitting error was less than 1%, and the water body was 8 times, which was basically consistent with the dynamic recognition of water body.

![Sedimentary facies model](image1)

![Porosity model](image2)

![Permeability model](image3)

![Gas saturation model](image4)

**Figure 1** Fine geological model of block X2 in XS gas field

3.2. Fitting bottom water gas reservoir history
On the basis of fine geological model, ECLIPSE software was used to conduct historical fitting for
block X2 of XS gas field, where the phase permeability curve and PVT curve were shown in figure 2.

![Relative permeability curve](image1)

![PVT Curve](image2)

**Figure 2** Fluid property curve of block X2 in XS gas field

The historical fitting results of gas production, cumulative gas production and pressure in block X2 of XS gas field are shown in figure 3. The X2 block of XS gas field has been put into production since October 2009. As of December 2018, the actual production is \(1374.26 \times 10^8\) m\(^3\), and the fitting cumulative gas production is \(1365.45 \times 10^8\) m\(^3\), meeting the fitting accuracy requirements. The actual formation pressure is in line with the fitting trend of formation pressure. The result of historical fitting is good, and the mathematical model can improve the theoretical basis for the subsequent reasonable gas recovery rate and the adjustment scheme.

![Fitting curve of gas production](image3)

![Fitting curve of cumulative gas production](image4)

**Figure 3** Historical fitting curve of block X2 in XS gas field

4. Research on reasonable gas recovery rate and adjustment scheme

4.1. Demonstration of reasonable gas recovery rate

Under the current well pattern conditions, the reasonable gas recovery velocity is demonstrated. The higher the gas recovery velocity, the shorter the stable production time (FIG. 4). The degree of production is greatly reduced (Table 1). It is demonstrated that the current reasonable gas recovery velocity of the gas reservoir is 2.5%.

![Reasonable gas recovery velocity relation curve](image5)

**Figure 4** Reasonable gas recovery velocity relation curve in block X2 of XS gas field

| Gas recovery rate | Stable time | Degree of production during stable production period | Final recovery |
|------------------|------------|-----------------------------------------------------|---------------|
| %                | %          | %                                                   | %             |
| 2.0              | 8          | 53.35                                               | 74.05         |
| 2.5              | 6          | 49.67                                               | 73.01         |
| 3.0              | 4          | 49.22                                               | 68.96         |
| 3.5              | 3          | 47.88                                               | 62.9          |

**Table 1** Comparison of development indexes of different gas recovery rates in gas reservoirs
4.2. Study on adjustment scheme of bottom water gas reservoir

According to the law of the bottom water gas reservoir, on the basis of the gas reservoir geology and dynamic analysis, the adjustment scheme of local drainage, the switch well of the water well and the sealing of the local water invasion channel are studied.

4.2.1. Research on local drainage mechanism of bottom water gas reservoir

According to the dynamic analysis and production logging results, 6 drainage wells were deployed in the part of the gas reservoir where the water invasion was large (Figure 5). It was demonstrated that the reasonable displacement was $6400\text{m}^3/d$ (Figure 6). By comparing the development indexes (Table 2), the recovery rate of the gas reservoir was increased by 0.63%, but the displacement was large and the drainage was less feasible due to the difficulty of surface treatment.

![Figure 5 profile of block X2 in XS gas field](image)

![Figure 6 Relation between gas reservoir displacement and degree of production](image)

| Table 2 comparison of local drainage development indexes of gas reservoirs |
|------------------------------------------------|
| Scheme design idea | Stable time a | Final recovery % | Cumulative water yield $10^4\text{m}^3$ |
|---------------------|--------------|------------------|---------------------------------|
| undrained           | 6            | 73.01            | 504.58                          |
| Drainage 3200m$^3$/d| 6            | 73.27            | 2475.43                         |
| Drainage 6400m$^3$/d| 6            | 73.64            | 3250.91                         |
| Drainage 10800m$^3$/d| 6          | 73.69            | 4453.27                         |

4.2.2. Study on the well switch scheme of water breakthrough wells

In the process of mining, after water breakthrough in some wells of the gas reservoir, it is necessary to demonstrate whether to continue production or shut down. Two schemes are set up. Plan 2: when the daily water output of a single well exceeds 200m$^3$, namely shut-in (Table 3), the recovery rate of continuous production is improved, but the cumulative water production is greatly increased, as shown in Figure 7. Therefore, economic benefit evaluation is required for shut-in or continuous production after water breakthrough of the gas well.

![Daily production curve](image)

![Cumulative yield curve](image)

| Table 3 comparison of switch well indexes after water breakthrough in gas reservoir |
|------------------------------------------------|
| Scheme design idea | Stable time a | Final recovery % | Cumulative water $10^4\text{m}^3$ |
|---------------------|--------------|------------------|---------------------------------|
| Plan 1              | 6            | 73.01            | 933.62                          |
| Plan 2              | 5            | 72.67            | 489.26                          |
4.2.3. **Study on the mechanism of blocking water invasion channel**

According to the research results of reservoir characteristics, the main water invasion channels in the gas reservoir were blocked for demonstration. Two schemes were set up. Plan 2: the water-invaded channel continues to produce (table 4). After the water-invaded channel is blocked, the recovery efficiency is improved and the water yield is significantly reduced (figure 8).

![Daily production curve](image1)

![Cumulative yield curve](image2)

**Figure 8 development effect diagram of blocked water invasion channel in block X2 of XS gas field**

| Scheme design idea | Stable time a | Final recovery % | Cumulative water yield $10^3 m^3$ |
|-------------------|--------------|-----------------|----------------------------------|
| Plan 1            | 6            | 73.01           | 504.58                           |
| Plan 2            | 7            | 73.37           | 409.23                           |

4.3. **Study on single well adjustment scheme of bottom water gas reservoir**

On the basis of fine characterization of faults and micro-faults, combined with geological and dynamic analysis results, three water invasion modes were studied in the water breakthrough wells in block X2 of XS gas field (Figure. 9). Single well adjustment scheme was studied for different water invasion modes.

![Gas saturation profile](image3)

**Figure 9** gas saturation profile in block X2 of XS gas field

4.3.1. **study on adjustment scheme of bottom water channeling upward along faults and fractures**

In well X32, where the bottom water moves upward along faults and fractures, the water control
methods such as controlling production, blocking perforating sections and blocking water invasion channels of fault fractures are demonstrated (Table 5). After blocking the water invasion channels of faults, the gas production per well increases by $14.58 \times 10^8 \text{m}^3$, and the cumulative gas production of gas reservoir increases by $7.39 \times 10^8 \text{m}^3$, with obvious effects (figure 10).

![X32 well daily production curve](image1) ![X32 well yield curve](image2)

Figure. 10 effect curves of different adjustment measures in well X32

**Table 5 comparison of effects of different adjustment measures in well X32**

| Scheme design idea                                           | Single well indicators | Gas reservoir indicators |
|--------------------------------------------------------------|------------------------|-------------------------|
|                                                              | Cumulative gas production $10^8 \text{m}^3$ | Cumulative water yield $10^4 \text{m}^3$ | Recovery degree % | Cumulative water yield $10^4 \text{m}^3$ |
| Gas well shut-in after water breakthrough                    | 16.00                  | 11.25                   | 72.98             | 504.65                        |
| Control the production of gas well after water breakthrough  | 17.32                  | 43.72                   | 73.00             | 504.58                        |
| After the gas well water plug out of the water section to continue production | 20.52                  | 22.32                   | 73.06             | 503.01                        |
| The broken water invasion channel is produced after water breakthrough | 30.58                  | 17.03                   | 73.16             | 498.02                        |

4.3.2. study on the adjustment scheme of the relatively high permeability band water inlet pattern

With respect to the X42 well with a relatively high permeability strip, the water control methods such as controlling pressure difference and plugging the high permeability strip are demonstrated (Table 6). After plugging the high permeability strip, the cumulative gas production of the single well and gas reservoir increases, and the cumulative water production decreases obviously. The sealing effect of the high permeability strip is good (Figure 11).

![X42 Daily production curve](image3) ![X42 Yield curve](image4)

Figure. 11 Effect curves of different adjustment measures in well X42

**Table 6 comparison of effects of different adjustment measures in well X42**

| Scheme design idea                          | Single well indicators | Gas reservoir indicators |
|---------------------------------------------|------------------------|-------------------------|
|                                                              | Cumulative gas production $10^4 \text{m}^3$ | Cumulative water yield $10^4 \text{m}^3$ | Recovery degree % | Cumulative water yield $10^4 \text{m}^3$ |
| Control production after water breakthrough in gas well | 25.96                  | 58.01                   | 73.00             | 504.58                        |
| Gas well plug high permeability strip production | 29.00                  | 4.70                    | 73.04             | 474.01                        |
5. Conclusion

(1) Fine numerical simulation of gas reservoir shows that the reasonable gas recovery rate of bottom water gas reservoir in block X2 of XS gas field is 2.5%.

(2) The study on the overall adjustment scheme of bottom-water gas reservoir in block X2 of XS gas field shows that the reasonable local displacement of gas reservoir is 6400m³/d, and the recovery rate of gas reservoir increases by 0.63%. After water breakthrough in gas Wells, the Wells are opened to continue production, and the development effect is good, but the cumulative water production has increased significantly, and the plan should be made according to the results of economic benefit evaluation; When the gas reservoir is exposed to water, the main water invasion channel is blocked and the gas recovery effect is good.

(3) The results of single well measure adjustment show that the effect of continuous production is better than that of well shut-in after water breakthrough. Sealing out water level has certain effect on gas well recovery, which is mainly based on the main water invasion channel measures such as sealing fracture and hypertonic strip.

Acknowledgments

This study was supported by Major Project of China National Offshore Oil Corporation 13th five-year plan (Grant No. CCL2018ZJFN0462), National Natural Science Foundation of China (Grant No.: 51774095), and PetroChina Innovation Foundation (Grant No.: 2018D-5007-0215).

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