Research on Water Invasion Mode and Water Control Counter Measures of Geological MX Gas Reservoir

Jifu Ruan¹, Jin Yi¹*, Lianlian Zhou¹, Xiaofei Gan¹, Jingxin Ruan², Yuhang Liu²

¹Chuanzhong Oil and Gas Field, Southwest Oil and Gas Field, PetroChina
²Southwest Petroleum University, Chengdu, China

*Corresponding author: yijinpost@petrochina.com.cn

Abstract. The MX gas reservoir is a typical carbonate gas reservoir and there are three types of water production characteristics in producing wells during the development process: fast rising type, slow rising type and stable type. The overall water invasion mode is dominated by the edge water invasion mode, with four types of water invasion modes including bottom water cone type, edge water finger type, edge water tongue type and native movable water tongue type. In this paper, numerical simulation techniques are used to investigate water management countermeasures for MX gas reservoirs based on the dynamic identification of water invasion. The results show that, after optimisation of the drainage and water control plans, the gas reservoir can produce steadily until the end of 2025 at a recovery rate of 3.06%, extending the time of steady production by about 9 months. In view of the relatively uniform advancement of fracture water channel and edge water into the interior of the gas reservoir, it is feasible to adopt active drainage and edge water control measures respectively to reduce the risk of water intrusion in the gas reservoir and ensure stable gas production.

Keywords: MX gas reservoirs, water invasion modes, water invasion modes, water management countermeasures.

1. Introduction

The MX gas reservoir is a low permeability carbonate gas reservoir located in the Weiyuan-Longnvshi tectonic group in the gently sloping tectonic zone of the ancient Longzhong, Central Sichuan. In general, it has the characteristics of high in the west and low in the east, high in the middle and low on both sides in the north-south direction. The gas reservoir has entered the stage of stable production. Through years of development, rich results have been achieved in static information such as geological features and geological reserves of the block. With a progressive understanding of the geology and development characteristics, it has been found that water invasion of gas wells is becoming a major factor affecting the smooth and efficient production of MX gas reservoirs. At present, there are problems such as large changes in the gas-water relationship in gas reservoirs, the obvious impact of water production on gas well capacity, and the need for continuous optimisation of water management solutions.
The 40-60% recovery rates for watered gas reservoirs are significantly lower than the 80-95% recovery rates for pure gas reservoirs, with water invasion significantly reducing the recovery rates of gas reservoirs [1]. Objective and timely prediction of water intrusion dynamics, understanding of water invasion characteristics of water-driven gas reservoirs can help to develop gas well working system, optimize water control and gas recovery measures, and prolong gas recovery time, which is of great significance to gas reservoir development [2-4]. Most researchers usually use numerical simulation method to study the water invasion mode of gas reservoir [5-13]. Numerical simulation, as a reliable and practical simulation technology, has become an important tool for reservoir dynamic analysis [14-17], which can provide reasonable and effective specific countermeasures for the comprehensive optimization of gas reservoir development plans [18].

2. Gas Reservoir Overview

The top structure of the MX gas reservoir extends in a north-easterly direction, with a length of 41.2km, a width of 8.3 to 14.1km, a trap area of 510.9km2 and a closure height of 145m. It is dominated by carbonate platform sedimentary system. The lithology is mainly grain dolomite, arenaceous dolomite, oolitic dolomite, argillaceous limestone, argillaceous dolomite with a small amount of sandstone. The depth of burial is around 4500 to 4800m, and the overall thickness of the layer is distributed around 80 to 100m, with little variation in thickness, mainly of the fracture-pore (hole) type and pore type. According to sample analysis, the average porosity of MX gas reservoir is about 5.19% and the permeability is 9.65mD. It is a low porosity, medium and low permeability reservoir. The pressure in the middle part is 75.74-76.09mpa, the pressure coefficient is 1.64-1.69, and the formation temperature is 138.5-145.8 ℃. It is a high temperature and high pressure gas reservoir. By the end of 2020, 54 wells were opened in the MX gas reservoir, producing 2,628.42×10^4 m^3 of gas and 1,541.83m^3 of water per day, with a production water to gas ratio of 0.587m^3/10^4m^3, cumulative gas production of 507.5×10^8 m^3 and cumulative liquid production of 136.39×10^4 m^3.

3. Study of water invasion mode

3.1. Single well water production characteristics

Produced water from the MX gas reservoir is mainly sourced from the MX9 well area, followed by the southern and northern parts of the MX8 well area. The water-gas ratio change curve of water-producing wells shows that the water-producing characteristics of water-producing wells can be divided into three main categories: After the first type of well produced water, water production increased rapidly while gas production decreased rapidly, as shown in Fig 1 (a). After the second type of well produced water, the curve rose more slowly than that of the first type, indicating a long period of intensified water invasion and a slight decrease in gas production, as shown in Fig 1 (b). The curve of the third type of well shows that the water production is relatively stable after water occurrence, the water-gas ratio basically remains low, and the gas production slightly decreases, as shown in Fig 1 (c).

![Figure 1. Single well water to gas ratio curve for MX gas reservoir.](image-url)
3.2. Typical well water invasion mode

The spatial distribution of gas and water can be divided into two types of reservoirs: marginal water
reservoirs and bottom water reservoirs. The five main sources of produced water from gas wells are
internal sequestration, condensate, interbedded water, marginal bottom water and rejection fluid. Gas
wells with different water source types have different water production modes, and reservoirs with
different stratigraphic conditions have different water invasion models.

Combined with logging and seismic interpretation, reservoir-related parameters and gas-water
relationships were obtained, and the formation water wells in the MX gas reservoir are mainly of Edge
water finger type and edge water tongue type

(1) Edge water finger type

The fractures between the water zones of the MX2 and MX3 wells are well developed, and the
production shows a very rapid increase in water volume and a decreasing trend in daily gas production
after the water appeared.

![Figure 2. FRS fracture prediction distribution diagram of well group MX1~3.](image)

![Figure 3. Production curve of well MX3.](image)

(2) edge water tongue type

Geologically, well MX15 has a geological basis for connectivity with the western trench and the
eastern partially sealed water area; A comparison of multiple well test data shows that the pressure
derivative curve in the late stage of the well gradually upturned and the permeability of the far well
area decreased, showing the characteristics of edge water water invasion; since 2018, the water
production, production water to gas ratio and water chemistry characteristic parameters of the well
have all shown an increasing trend.

![Figure 4. Production-water chemical characteristic curve of well MX15.](image)

The study of the water invasion modes shows that the overall intensity of water invasion in the gas
reservoir is weak to moderate, while the water producing single wells show moderate to strong water
invasion. There are three types of water production characteristics in producing wells: fast rising, slow rising and stable. Gas reservoirs face a range of problems such as high local recovery rates, high water and gas energy and intensity, and complex water invasion modes, so there is an urgent need to carry out research on the optimisation of water management countermeasures.

**Figure 5.** MX15 well water flooding front contrast diagram.

### 4. Optimization of water invasion control strategy for gas reservoir

On the basis of dynamic analysis, optimized research on water management countermeasures was carried out based on numerical simulation technology. With the objectives of reducing water invasion hazards, ensuring stable gas reservoir production and improving gas recovery, the technical countermeasures for water management in gas reservoirs were optimised based on continuous follow-up studies.

#### 4.1. Typical well water invasion mode

The MX gas reservoir is developed with high water energy in the early stage, high local recovery rate of the gas reservoir, large water storage capacity and high water and gas energy and intensity. Based on the single well production, the gas well allocation was reduced and six scenarios (100, 90, 80, 70, 60 and 50 Bcf of gas per year) were designed to carry out the gas recovery rate optimisation study and the simulation results are shown in Fig 6 below.

**Figure 6.** Curves of daily gas production, pressure and daily water production at different gas production speeds.
As the daily gas production decreases, the time of stable production is extended, but the degree of eventual recovery is reduced. In order to safeguard gas production from the reservoir while extending the stable production time as much as possible, a comprehensive analysis concluded that Option IV (7 billion cubic metres of gas per annum) is recommended. This option reduces the production allocation of gas Wells in the low permeability zone, and the production Wells are properly controlled (but insist on water production), which can extend the stable production period of the gas reservoir to 70 months, with a large degree of recovery and a smaller rate of decline and water production during the declining period.

4.2. Typical well water invasion mode

(1) Optimization of well production control at water occurrence risk

Well MX102 is located at the edge of the well area adjacent to the edge water or gas-water transition zone. Water suddenly occurs during the production of the gas well, and the water volume increases rapidly, and the daily production of gas presents a downward trend. There is a potential risk of water invasion and the type of water invasion is relatively homogeneous. The effect of the gas extraction rate of the well group on the rate of water invasion at the margin is considered by changing the production allocation to the neighbouring wells MX4-1 and MX4-2 while maintaining a production rate of 30 x 10⁴m³/d in MX102.

As can be seen from Figure 4-4, the cumulative gas production from the MX102 well decreases significantly as the rate of gas recovery from the MX4 well group increases, which confirms that the MX102 well has better reservoir continuity with the north-western highly permeable water body and that increased gas production within the gas reservoir will draw the edge water to the interior of the gas reservoir more quickly.

Figure 7. Comparison of stable production time under different schemes

Figure 8. Comparison of development indicators under different schemes

Figure 9. Comparison of cumulative gas production predicted at the end of the period of mx102 well under different gas production rates of 4mx4 well group.
After a comprehensive analysis, it is considered that the edge water in the MX9 well area is advancing relatively evenly from the MX102 well to the interior of the gas reservoir. It is recommended that the MX102 well should still produce at $30 \times 10^4$ m$^3$/d and do a good job of controlling the edge water, while the gas producing wells in the interior of the gas reservoir can be considered to lower production appropriately to slow down the rate of water invasion in the gas reservoir.

(2) Production and drainage of water production wells with liquid

For the MX1~4 well group where water invasion has occurred, the type of water invasion in this well group is fracture water channeling, which is more harmful to the gas reservoir and requires active water treatment countermeasures. It is necessary to take active water control measures, and it is considered that MX2 well and MX3 well in this well group should take active water control measures with artificial drainage. Four well groups, MX1, MX2, MX3 and MX4, were used for comparative analysis to simulate and predict artificially assisted drainage measures for MX2 and MX3 wells in 2021 and 2022 and 2023 respectively, and to analyse the impact of drainage timing on production.

As shown in Figures 4-6, the earlier the well group starts to adopt artificial drainage measures, the more obvious its impact on the reservoir production effect and the greater the cumulative gas production. As the drainage scale increases, the growth trend becomes slower when the drainage scale exceeds 300 m$^3$/d.

![Figure 10. Well location map of well group MX1-4.](image1)

![Figure 11. Recurrent gas production of MX2 well with different drainage times and drainage intensities.](image2)

Similarly, the earlier the MX3 well started to take the artificial drainage measures, the more stable the production, the later the drainage time, the more serious the gas reservoir water flooding. Even if the displacement is increased, not enough gas can be brought out, which can be considered as soon as possible drainage, drainage intensity of 400 m$^3$/d.

![Figure 12. Accumulated gas production at different drainage times and drainage intensities of well MX3.](image3)
After comprehensive analysis, it is believed that it is feasible for the MX1~4 well group to take artificially assisted drainage measures to actively drain the wells, keeping the MX1~4 well group to produce with water first and play an active drainage role. When its wellhole accumulation of liquid as early as possible to take artificially assisted drainage measures to make it active drainage, MX2 well, MX3 well maximum drainage scale of 300, 400m³/d respectively.

(3) Optimization of new drainage wells

The MX5 well in the MX9 well area is close to the gas-water boundary and is located on the water intrusion channel where the edge water intrudes from the well to the interior of the gas reservoir, with a potential risk of water intrusion of a relatively uniform type. A new well is considered to be deployed on this water intrusion channel, i.e. in the transition zone outside the MX5 well, to evaluate its drainage effect.

A group of five wells, MX1, MX2, MX3, MX5 and MX6, was used for comparative analysis to simulate the drainage effect of deploying a drainage well, P1, in the transition zone of MX5 well and its drainage scale. The results of the simulation are shown in Figure 4-9. Dewatering in the transition zone has a definite impact on the cumulative gas production of the whole well group, but beyond 200m³/d leads to poor production results.

Therefore, for the water invasion channel, the deployment of new Wells in the transition zone around well MX5 to take active drainage measures can optimize the development effect of the gas reservoir, but the increased investment is relatively large.

After comprehensive analysis, it is considered that the predicted time of water occurrence in MX5 well is the end of 2024. It is suggested that the water invasion channel should first use the natural energy of MX5 well to carry liquid production in the first phase to delay the further invasion of formation water into the gas reservoir; later, if the water invasion intensifies, MX5 well can be considered to take artificially assisted drainage measures to drain the water; when the artificially assisted drainage effect of MX5 well is not obvious, a new drainage well can be considered to be deployed in the gas-water transition zone, with a proposed drainage intensity of 200m³/d, which can reduce the intensity of water invasion of edge water along the high permeability layer pointing into the invaded gas reservoir.

The results of the optimization of the base scheme with the above water control scheme and comprehensive simulations show that the optimized scheme can stabilize production until the end of 2025 at a gas recovery rate of 3.06%, extending the stabilization time by about 9 months.

5. Conclusions

In this paper, a study of water invasion patterns and the application of high precision numerical simulations was carried out for MX gas reservoirs, and the following conclusions can be drawn from the results of the study:
There are three types of water production characteristics in MX gas reservoir producing wells: fast rising type, slow rising type and stable water production type. Combining well logging, seismic interpretation, reservoir-related parameters and gas-water relationships, MX producing formation water wells are mainly of the edge water finger type and edge water tongue type.

In view of fracture water channeling type well group, artificial drainage measures are adopted to actively drain water. It can produce with water in advance to play the role of active drainage. When the fluid accumulates in the wellhole, it can take artificial drainage measures as soon as possible to make it active drainage. For well groups with a greater risk of water invasion and relatively uniform water invasion, if the effect of artificial assistance in drainage is not obvious, the deployment of new drainage wells in the gas-water transition zone can be considered, which can reduce the intensity of water invasion along the high permeability layer finger into the invaded gas reservoir. In view of the relatively uniform advance of the edge water into the gas reservoir, it is suggested to control the edge water well well, and reduce the production of the gas producing Wells in the gas reservoir appropriately to delay the water invasion rate of the gas reservoir.

Under the condition of the optimal gas production rate of 3.06%, comprehensive water control measures such as production control and postponement of water invasion, fluid production in the producing well and drainage of new Wells are carried out for MX gas reservoir. Compared with the current production plan, the stable production time of the gas reservoir can be extended by about 9 months, and the cumulative recovery degree can be increased by 5% by the end of 2025.

For this kind of carbonate rock, the focus of gas reservoir water control should be to consider the active production reduction of the risk Wells in the side, and at the same time to take the strategy of combining water control with active drainage. This can prolong the anhydrous gas production period, prevent water from accelerating into the gas reservoir along the water invasion advantage channel, delay the water invasion rate in the middle of the gas reservoir, and improve the gas reservoir recovery factor.

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