Research on Water Influx Issues in Carbonate Reservoir Development

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Abstract: The issue of water encroachment in the development of carbonate reservoirs has always been one of the significant factors limiting the effectiveness of reservoir development. The impact of water encroachment on well productivity cannot be ignored, making the study of water encroachment in carbonate reservoirs of great theoretical and practical significance. In this study, we focused on the problem of severe water encroachment in the fringe well group of the MX reservoir, and applied dynamic analysis and numerical simulation techniques to explore practical water management strategies. The research results indicate that in strong water encroachment reservoirs, active drainage from peripheral wells can consume water energy, reduce the pressure differential between gas and water zones, slow down the water encroachment rate, and significantly delay the occurrence of water breakthrough within the reservoir. This study provides technical references for the rational and effective development of strong water encroachment reservoirs.

Keywords: MX reservoir, Water encroachment, Water management strategies, Numerical simulation.

1. Introduction

The Sichuan Basin is an important natural gas production area in China, and the MX reservoir, as one of the largest carbonate reservoirs in the basin, contributes significantly to the natural gas production and reserves. In some areas of this block, the development of fractures in the reservoir has led to water encroachment becoming a major factor affecting the stable and efficient production of the MX reservoir. Currently, there is a high risk of water flooding in the peripheral wells of this block, and the impact of water production on the overall block productivity is increasing year by year. Relying solely on post-production water management measures is challenging to cope with unforeseen circumstances[1]. In order to increase the recovery rate of the MX reservoir and achieve efficient overall development of the reservoir, this study combines dynamic analysis of water encroachment with three-dimensional fine-scale numerical simulation techniques. It predicts the production characteristics of the current drainage and gas recovery scheme 15 years later, optimizes production allocation plans, extends the stable production period of high-yield wells, and restores the gas production capacity of water-affected wells, thereby improving the utilization efficiency of water-flooded wells[2].

2. Macro Mechanism of Reservoir Water Encroachment

Water encroachment at the macro level manifests as the intrusion of water into the reservoir, leading to three phenomena: gas confinement, compartmentalization, and water flooding, which transform recoverable gas into "dead gas." The reasons for this are: (1) During reservoir development, under the action of production pressure differential, the large fractures are preferentially occupied by formation water, resulting in the trapping of natural gas in the matrix pores[3]. (2) After water encroachment, the high-permeability channels are filled with water, deteriorating the connectivity properties of the reservoir. Moreover, as the reservoir is depressurized during gas production, rock elasticity expands and fractures close, leading to reduced reservoir connectivity and even segmentation of the reservoir, forming "dead gas" blocks[4].

3. Dynamic Analysis of the MX Reservoir

The MX reservoir is a low-porosity and medium-to-high-permeability carbonate reservoir. Pore volume analysis of small plug samples shows porosity ranging from 1.96% to 17.53%, and permeability ranging from 0.0001 to 263mD. Multiple-scale fractures are developed in the study area, with fracture apertures ranging from 0.001 to 0.102mm. In the early stage of reservoir development, stress sensitivity and heterogeneity are significant. The reservoir has sufficient energy to produce fluids, but increasing production rates result in early water breakthrough and lower cumulative gas production in the wells.

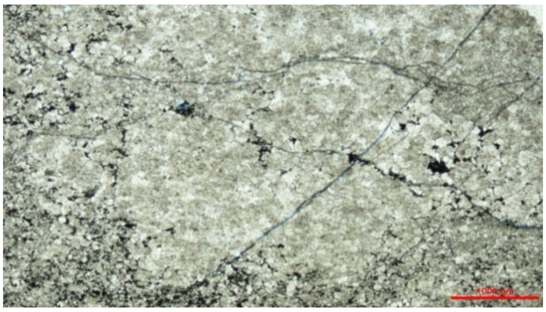

Figure 1. The cast thin section of reservoir section sample

The MX1 well group is a strong water encroachment well group with developed reservoir fractures and severe water encroachment. It exhibits evident characteristics of fracture water channeling, rapidly producing water after commencement of production. The water production rate significantly varies with gas production, and the wells maintain water production capability for a considerable period of time after water breakthrough. The water encroachment direction is from the MX1-2 and MX1-3 wells towards the MX1-1 well.

Among them, the well test results of the MX1-2 well indicate high permeability characteristics with well-developed reservoir fractures. The initial stable production rate is 134×104m3/d, and water production starts after 53 days. The water production rapidly increases after water breakthrough, but short-term water production decreases when controlling individual well and well group production rates. Subsequently, the water-gas ratio increases rapidly due to the infiltration of formation water along high-conductivity fractures, resulting in a small production pressure differential for this gas well.The MX1-3 well has an initial stable production rate of $52.3\times10^4 m^3/d$, and water production begins after 163 days. The water production rapidly increases after water breakthrough, and the water-gas ratio continues to rise even after production control.

By applying various methods such as material balance and Mbal, the calculation of the water body near the well group was conducted, yielding a range of $7963\times10^4 m^3$ to $11375\times10^4 m^3$, with a water encroachment volume of $287\times10^4 m^3$ to $374\times10^4 m^3$. According to Equation (1)[5], the water encroachment displacement coefficient for this well group is calculated to be 0.584. The comprehensive analysis indicates that the water body reserves near the well group are significant, exhibiting high water activity, and belong to a strong water encroachment reservoir. Currently, this block is in the early stage of water encroachment, thus necessitating early detailed characterization and the formulation of corresponding water management plans.

$$I = \frac{W_e - W_p B_w}{G_p B_{gi}} \quad (1)$$

4. Numerical Simulation of Drainage Gas Production in Strong Water Encroachment Well Group

4.1. Model Establishment

To effectively address the issue of strong water encroachment in the MX gas reservoir, this section conducts numerical simulation of drainage gas production in the strong water encroachment well group. Advanced numerical simulation techniques are employed, combined with the geological characteristics and water encroachment mechanisms of the MX gas reservoir, to simulate and evaluate the drainage effectiveness of the strong water encroachment well group. Based on the production dynamic data of the target well group, a dual-porosity and dual-permeability black oil model is established to track and evaluate the production dynamics of the strong water encroachment production wells[6-7].

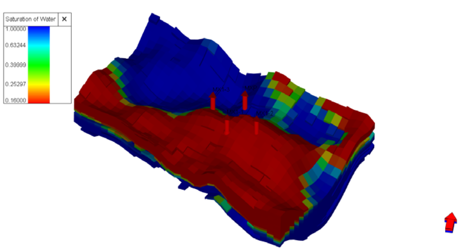

Figure 2. The 3D model of matrix of study well group

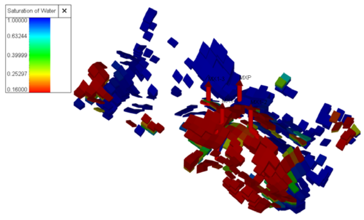

Figure 3. The 3D model of fractures in the study well group

4.2. Model Analysis

In order to address the potential issue of strong water influx in the MX reservoir 15 years later, this study designed multiple scenarios and conducted numerical simulations to predict various production and development indicators. Considering the characteristics of the dual-porosity and dual-permeability carbonate gas reservoir, the model was adjusted and simulated, and the results showed a good fitting effect of the model.

The internal well MX1-1 was used as a gas production well, while the external wells MX1-2 and MX1-3 were designated as active water drainage wells. The simulation results indicated that the effective drainage from MX1-2 and MX1-3 delayed the ingress rate of the water front. During the simulation process, it was observed that insufficient drainage occurred when the drainage rate of MX1-2 exceeded 280 m^3/d and MX1-3 exceeded 330 m^3/d. Therefore, it is recommended to set the drainage rate of MX1-2 between 220-330 m^3/d and MX1-3 at 330 m^3/d.

The profile view reveals a reduction in water saturation at the water-drive front, indicating that active drainage of the underlying water layer in the edge water zone can consume water energy. However, the drainage volume needs to be controlled to achieve effective water management. When the permeability of the underlying water layer is higher than that of the gas layer, simultaneous production of gas and water can lead to rapid water flooding of the gas well, thereby negating the water management effect.

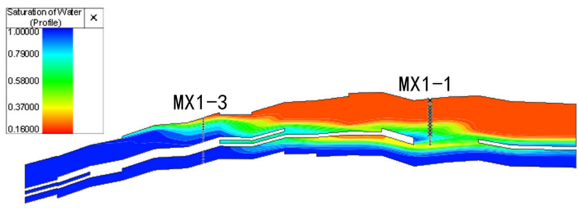

Figure 4. The cross profile of connecting well without drainage measures

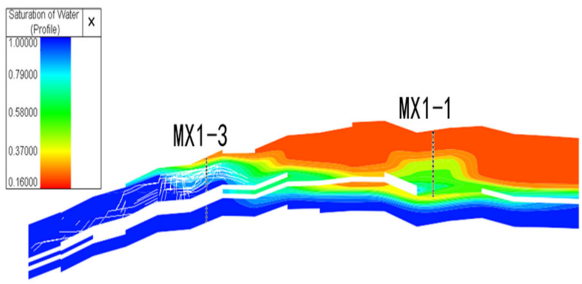

Figure 5. The cross pfofile of connecting well cluster drainage 600 cubic meters per day

5. Conclusion

The numerical simulation results of this study provide water management strategies for addressing the potential issue of strong water influx in the MX reservoir 15 years later. By adjusting the drainage scheme appropriately, the water ingress rate can be effectively delayed, reducing adverse impacts on the gas reservoir and providing technical support for the efficient development of the MX reservoir. The following conclusions can be drawn:

(1) The internal well MX1-1 serves as the gas production well, while the external wells MX1-2 and MX1-3 act as active water drainage wells, demonstrating good drainage effectiveness in the simulation and effectively delaying the ingress rate of the water front.

(2) During the simulation, it was observed that insufficient drainage occurs when the drainage rate of MX1-2 exceeds 280 m^3/d and MX1-3 exceeds 330 m^3/d. Therefore, it is recommended to maintain the drainage rate of MX1-2 within the range of 220-330 m^3/d and set the drainage rate of MX1-3 at 330 m^3/d.

(3) The profile view reveals a reduction in water saturation at the water-drive front, indicating that active drainage in the edge water zone can consume water energy. However, it is crucial to control the drainage volume during water management. Particularly, when the permeability of the underlying water layer is higher than that of the gas layer, simultaneous production of gas and water may lead to rapid water flooding of the gas well, counteracting the desired water management effect.

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