Fine numerical simulation of deep carbonate gas reservoir in northwest Sichuan

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Abstract. Qixia Formation in northwest Sichuan has a complex structure, ultra-deep burial, high temperature and high pressure, thin reservoir and fractures development, and it is difficult to simulate the gas reservoir numerically. Based on existing geological understanding, in this paper, the tracking attribute parameters of three-dimensional seismic data bodies are optimized by ant tracking technology. Through the automatic extraction crack system of differential bodies, a three-dimensional geological model considering natural fractures is established. Using embedded discrete cracks and MRST numerical simulation open-source program, a numerical simulator of deep carbonate gas reservoirs in northwest Sichuan has been formed, and the development mechanism of Qixia Formation in northwest Sichuan is demonstrated. The research work in this paper has a certain theoretical guiding significance for the efficient development of deep carbonate gas reservoirs in northwest Sichuan.

1. Overview of Qixia Formation Gas Reservoir Exploration and Development

Geographically, the Beas Stone block is mainly located in Jiange County, Zhaohua District and Lizhou District of Guangyuan City, Sichuan Province. The structure is located in the transition zone between the Longmenshan fault fold belt in northwestern Sichuan and the low gentle zone of the Paleo-central depression in the northwest of the Sichuan Basin. Piedmont fault fold belt on the south margin. The Qixia Formation gas reservoir in northwestern Sichuan has a complex structure, ultra-deep burial (over 7000m), high temperature and high pressure (formation pressure 95MPa, pressure coefficient 1.3, formation temperature 150°C), medium sulfur content (0.4%), and thin reservoirs (10-25m), with the characteristics of multiple storage spaces (holes, caves and fractures are all developed) [1].

Since the discovery of the gas reservoir, many wells have obtained high-yield gas flows. In 2018, the block declared tertiary reserves of 116.945 billion cubic meters, of which the controlled reserves were 81.13 billion cubic meters. The trial production plan of the Qixia Formation in the Shuangtan 1 well area has been approved by the stock company. Well Biyu 001-1 has a good test production effect. It has maintained a stable production of 300,000 cubic meters per day until November 2017. The oil pressure has continued to be stable, and the unit pressure drop reserves are large. It shows broad prospects for exploration and development, which will ensure the Sichuan Basin by 2025. One of the key areas to achieve a 40 billion strategic atmosphere area annually [2, 3].
2. Establishment of 3D fracture model of Qixia Formation gas reservoir
Using the existing three-dimensional seismic data volume, combined with the ant tracking algorithm, by analyzing the influencing factors of the ant tracking attribute body, the ant tracking attribute parameter setting suitable for the Qixia Formation gas reservoir is selected. The shift is 2, the search step is 3, the illegal range is 1, the legal range is 3, the search termination threshold is 10, and the best difference body model is obtained [4].

According to the automatic fragment extraction technology, the three-micro fracture model of the research area is established, so as to realize the three-dimensional reconstruction of the local fracture system of the gas reservoir. [5] Based on the established fracture network, the oda algorithm in scale-up fracture properties is used to establish the fracture property model.

3. Three-dimensional numerical simulation mathematical model of Qixia Formation gas reservoir
For the problem of fluid seepage in large-scale fractures and small-scale fractures in carbonate gas reservoirs, it is handled by embedded discrete fractures. The flow of gas and water three-phase fluid in
the reservoir obeys Darcy’s law, and the seepage is isothermal; The gas and water phases are not mutually soluble; the rock reservoir is slightly compressible, and the fluid is compressible; the reservoir has heterogeneity and anisotropy, considering the influence of gravity and capillary force. According to previous research results, the mathematical model of condensate oil, gas and water three-phase seepage:

Water phase:
\[
\nabla \left( \frac{K(r)K_w}{B_w \mu_w} \nabla \Phi_w \right) = \frac{\partial}{\partial t} \left( \frac{\phi S_w}{B_w} \right) + Q_w + Q_{wv}
\]

Gas phase:
\[
\nabla \left( \frac{K(r)K_g}{B_g \mu_g} \nabla \Phi_g \right) = \frac{\partial}{\partial t} \left( \frac{\phi S_g}{B_g} \right) + Q_g + Q_{wg}
\]

Material conservation equation of discrete fracture fluid:
\[
\sum q_{g,f} + \sum q_{w,f} = \sum q_{mf}
\]

Saturation auxiliary equation:
\[
S_g + S_w = 1
\]

Oil and gas capillary force auxiliary equation:
\[
P_{eug} = P_g - P_w
\]

Water potential function:
\[
\Phi_w = P_w + \gamma_w Z = P_w - P_{gws} + \gamma_w D
\]

Gas potential function:
\[
\Phi_g = P_g + \gamma_g D
\]

Initial conditions:
\[
P(x, y, z, t) \mid_{t=0} = P_i, \quad S_g(x, y, z, t) \mid_{t=0} = S_{ig}
\]

Outer boundary condition:
\[
\frac{\partial \Phi_w}{\partial n} \mid_r = 0, \quad \frac{\partial \Phi_g}{\partial n} \mid_r = 0
\]

Inner boundary condition:
\[
Q(r = r_i, t) = \text{const}, \quad P(r = r_i, t) = \text{const}
\]

Where: 
- $D$——Height coordinates, m; 
- $\gamma_w, \gamma_g$——Respectively the relative density of water and gas, dimensionless; 
- $\mu_g, \mu_w$——Respectively the viscosity of the gas phase and the water phase, cp; 
- $K_{ego}, K_{ew}$——Are the relative permeability of gas-phase and water phase, Dimensionless; 
- $Q_g, Q_w$——Surface production of gas and water per unit volume of rock, m\(^3\)/d; 
- $B_g, B_w$——Volume coefficient of air and water phase, dimensionless; 
- $\varphi$——Porosity of rock, decimal; 
- $\Phi_g, \Phi_w$——Are the potentials of the gas phase and the water phase, m; 
- $S_{w,c}$——Irreducible water saturation, Decimal; 
- $S_g, S_w$——Gas and water phase saturation, Decimal; 
- $P_{cgw}$——Air and water capillary pressure, MPa; 
- $q_{mfw}, q_{mfg}$——The water and gas volumes of discrete fractures and gas reservoirs, m\(^3\)/d.

4. Qixia Formation gas reservoir development index prediction

Based on the Matlab language, an embedded discrete fracture numerical simulation model program system was constructed. According to the final result of the ant difference body, the fractures near the horizontal well were mainly digitized, and the staged fracturing horizontal well model was set up according to the on-site construction situation [6]. The conductivity and length of the artificial fractures are calculated. The specific realization process is shown in the figure:
Based on the embedded discrete fracture numerical simulation model program, numerical simulation models of different horizontal section lengths are set up, and the development index results of different horizontal section lengths are obtained. It can be seen from the prediction results that after considering embedded natural fractures, the pressure relief range of horizontal wells has changed from a traditional ellipse to an irregular polygon, which is more consistent with the actual reservoir pressure distribution. Besides, as the length of horizontal wells increases, single wells are exhausted. The gas production is relatively higher, but the increase in the later period slows down.

Figure 4. Numerical simulation process of embedded discrete fracture.

Figure 5. Schematic diagram of the distribution of the pressure drop vulnerabilities predicted by the different horizontal section length models.

Figure 6. Comparison of cumulative production under different horizontal section lengths.

Figure 7. Schematic diagram of optimization of different horizontal section lengths.
By comparing the development characteristics of similar domestic gas reservoirs, it is recommended to adopt the development strategy of "being fat first, then lean, achieving profitable development", which can be realized in the Shuangtan 1 well area (Shuangtan 12-Shuangtan 7-Shuangyu 132-Shuangtan 10 well area) Profitable development, and then implement rolling exploration near the Shuangtan 9 well area; adopt the method of "along the long axis, occupying high points", and locally can use double-row "Z"-shaped wells [7, 8]. Highly deviated wells are used for Type I high-yield areas, and horizontal wells are used for Type II and Type III areas. It is recommended that a reasonable well spacing is 1600-1800 meters, the gas production rate is controlled within 4%, and the recommended stable production period is 10-15 years. At the same time, the dynamic monitoring of well Shuangtan 10 should be done to find out the size of the water body and the law of water invasion. Based on the above development strategy demonstration, a fine numerical simulation of marine deep carbonate gas reservoirs in northwestern Sichuan has been carried out. The recovery rate of the Shuangtan 1 well area is 63%. The specific development indicators are shown in the table below.

### Table 1. Prediction results of development index for deep-seated carbonate gas reservoirs in northwestern Sichuan

| Plan number | Scheme I | Scheme II |
|-------------|----------|----------|
| Active area(km²) | 320 | 320 |
| Exploited reserves(10⁸m³) | 600 | 600 |

#### Design specifications

| Number of wells (ports) | Existing well |Exploratory well | Rolling evaluation well | Test well | New well | Takeover well | total |
|-------------------------|---------------|-----------------|------------------------|----------|---------|--------------|-------|
|                         |               |                 |                        |          |         |              |       |
| Daily gas production (10⁸m³/d) | 880 | 800 |
| Annual gas production (10⁸m³/a) | 29.6 | 27.5 |
| Gas production rate (%) | 4.5 | 4.3 |
| Wellhead constant pressure (MPa) | 20 | 20 |

#### Stable production period

| Start time (year. month) | 2020.01 |
| End time (year. month) | 2028.11 |
| Years of stable production (years) | 8.9 |
| Tired gas production at the end of the period (10⁸m³) | 273.33 |
| Recovery degree of reserves produced at the end of the period (%) | 45.6 |
| Liquid production at the end of the period (m³/d) | 117.05 |

#### Forecast period

| End time (year. month) | 2037.12 |
| Gas production at the end of the period (10⁸m³/d) | 50.06 |
| Tired gas production at the end of the period (10⁸m³) | 376.19 |
| Recovery degree of reserves produced at the end of the period (%) | 62.69 |
| Liquid production at the end of the period (m³/d) | 12.38 |

### 5. Conclusion

Using the existing 3D seismic data volume, combined with the ant tracking algorithm, by analyzing the influencing factors of the ant tracking attribute volume, the ant tracking attribute parameter setting suitable for the Qixia Formation gas reservoir is optimized, to obtain the best difference volume model. Extract the fragmentation technology and establish the three-micro fracture model of the research area, to realize the 3D reconstruction of the local fracture system of the gas reservoir.

The embedded discrete fractures are used for processing to solve the problem of difficult characterization of fluid seepage in large-scale fractures and small-scale fractures in carbonate gas.
reservoirs. It is recommended to adopt the development strategy of “first fat and then thin, achieving profitable development”. "Along the long axis, occupying high points" well layout method, using highly deviated wells and horizontal wells for development, a reasonable well spacing of 1600-1800 meters is recommended, the gas production rate is controlled within 4%, and the recommended stable production period is 10-15 years. The estimated recovery rate of Shuangtan 1 well block is 63%.

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