The reasonable development technology policy in sweet spot of tight gas reservoir

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Abstract

The development of sweet spot in tight gas reservoir is restricted by various factors, which cannot guarantee reasonable, efficient, and low-cost development, and technical policy of development is also immature. Through fine geological modeling and numerical simulation technology, and in accordance with the microseismic monitoring results, the pressure recovery test data, and analysis of the relationship between irreducible water saturation and permeability, history matching is conducted. On this basis, new wells can be designed and simulated again in this sweet spot. Finally, it is concluded that the horizontal well with staggered well pattern is the reasonable development of sweet spot, the reasonable well space is 600–800 m, the reasonable length of the horizontal section is 1200 m, and the reasonable initial gas production rate is $8 \times 10^4 \text{ m}^3/\text{day}$.

Keywords Sweet spot of tight gas reservoir · Microseismic monitoring · Numerical simulation · Well space · Length of the horizontal section · Gas production rate

List of symbols

t_p	The first longitudinal wave arrival time (s)
t_s	The first transverse wave arrival time (s)
V_p	Longitudinal wave velocity (ft/s)
V_s	Transverse wave velocity (ft/s)

Introduction

With the rapid decline of conventional oil and gas field production and the increase of human demand for oil and gas resources, the exploration and development of unconventional tight gas reservoirs have been paid more attention by an increasing number of countries around the world (Wang et al. 2016). Tight gas reservoirs are characterized by low porosity, low permeability, low abundance, strong heterogeneity, high development cost, and great economic risk. Therefore, for the development of tight gas reservoir, people tend to seek and develop the sweet spots (The

reservoir physical property and sand body distribution are better than tight gas reservoir but inferior to low-porosity and low-permeability gas reservoir.) (Li et al. 2012; Jia et al. 2012). However, the development of sweet spot is restricted by geological cognition, engineering factors, development technology and other aspects, and it cannot guarantee reasonable efficient and low-cost development; the development technology policy is immature (Holditch 2006; Khlaifat et al. 2011; Sun et al. 2011). In line with the microseismic monitoring results, the pressure recovery test data, analysis of the relationship between irreducible water saturation and permeability, history matching is conducted. On this basis, new wells are designed and simulated again in this sweet spot. Finally, the reasonable development technology policy is obtained, and it could be taken as reference for the same type reservoirs.

Reservoir description

This reservoir is deltaic front deposit and lithologic trap. The average porosity is 5.18%, the permeability is 0.01×10^{-3} – $1.8 \times 10^{-3} \mu\text{m}^2$, the reservoir buried depth is 2000–2350 m, and the reservoir effective thickness is 3–25 m; the dip angle is 1.3° – 4.2° , the faults are not developed. The reservoir has no obvious edge water, the average pressure in the central reservoir is 21.06 MPa, and the

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average pressure coefficient is 0.937. The effective area is 21.4 km² and geological reserve is 2.042×10^9 m³. As of December 2016, this area has drilled 7 vertical wells and 14 horizontal wells, in which 6 vertical wells and 11 horizontal wells have been put into production, the cumulative gas production is 3.6×10^8 m³, the well space is 400–600 m, and the length of the horizontal section is 300–1600 m.

Geological model and numerical simulation

On account of the detailed LWD data, core analysis data, logging data, gas test data, etc., the fine geological model of this sweet spot is built. The fine geological model grid is 10 m × 10 m × 1 m; the total grid number is 1.55×10^7 ; the geological reserve is 2.042×10^9 m³. Then the fine geological model is coarsened; the coarse geological model grid is 50 m × 50 m × 1 m; the total grid number is 6.2×10^5 ; the effective grid is 1.8×10^5 ; the geological reserve is 2.043×10^9 m³. The core and fluid parameters of the numerical simulation are measured in the laboratory (Table 1), and the relative permeability curve is normalized curve (Fig. 1).

The foundation of history matching

Microseismic monitoring

In this sweet spot, hydraulic fracture technology is the major measure to enhance gas production, and it has been widely used in modern petroleum industry, especially in the unconventional oil and gas area, for instance tight sandstone reservoir. The effects of hydraulic fracture directly affect the oil and gas production. With the real-time monitoring advantage, the microseismic monitoring technology is the best method to study the fracture extension rule, to control the fracture extension form, and to optimize the fracture parameters (Xu and Guo 2016; Wang 2013). The detector is placed in the monitoring well, and the generated microseismic

Fig. 1 Normalized relative permeability curve

signals are recorded during the fracture operation. The distance between the source and the detector is calculated:

$$d = \frac{(t_s - t_p) \times V_p \times V_s}{V_p - V_s} \quad (1)$$

The velocity model, time picking, and formation anisotropy parameters should be precise. Then through the use of nonlinear least square method or fast network search method, the analysis of the longitudinal wave holograms, the source direction is determined. One well's microseismic monitoring results in this sweet spot are shown in Table 2.

On the basis of the microseismic monitoring results of Table 2, the well's fracture length is 170–590 m, the fracture height is 55–90 m, the main fracture height (seismic moment height) is 15–30 m, the fracture width is 35–70 m, and the fracture trend is mainly distributed in 75°–90° north by east.

Pressure recovery test

After a well fractured and controlled to open drainage in the sweet spot, conduct pressure recovery test by shutting in well. Utilize pressure gauges to measure the static pressure and static temperature at different points; calculate the static pressure and static temperature of the middle reservoir. The use of the semilogarithmic curve and double-logarithm curve is to explain the near wellbore fracture condition, reservoir characteristics and reservoir property parameters, boundary characteristics, the effect of fracture, near wellbore pollution level, especially the skin factor (Zhuang 2004; Wang and Pan 2016).

Table 1 Input parameters of the simulation model

Number	Parameters	Value
1	Gas volume factor (rm ³ /sm ³)	0.00516
2	Gas density (kg/m ³)	0.585
3	Gas Z-factor	0.9022
4	Gas viscosity (mPa·s)	0.018
5	The salinity of formation water (mg/L)	33,842
6	Rock compressibility (MPa ⁻¹)	0.000182
7	Gas compressibility (MPa ⁻¹)	0.05
8	Reservoir temperature (°C)	64.5

Table 2 Results of microseismic interpretation

Sequence number	Fracture length (m)	Fracture height (m)	Fracture width (m)	Fracture trend (north by east/°)	Seismic moment height (m)
①	190	58	48	86	30
②	251	55	66	91	30
③	408	74	69	90	20
④	171	75	47	90	24
⑤	179	76	38	77	15
⑥	209	81	65	77	20
⑦	209	89	62	83	30
⑧	508	74	43	75	20
⑨	589	72	51	77	30

Fig. 2 Pressure changing range

For example, pressure recovery test was conducted in one well in 2016; the duration time was 578 h; the pressure changed from 8 to 21 MPa as shown in Fig. 2. After calculation, this well's skin factor was -4.6 .

Similarly, we get all production well's skin factor. The distribution frequency of the reservoir skin factor obtained from the 27 pressure recovery tests in the sweet spot is shown in Fig. 3.

Irreducible water saturation

In the development process of the tight sandstone gas reservoir, the well water production phenomenon has great influence on the well gas production. When water production is too large, the bottom hole pressure increases, the pressure difference between the reservoir and the bottom pressure reduces, the flow capacity of the reservoir gas decreases, and the well production declines rapidly (Li et al. 2013). The gas test data show that there is no water in the reservoir, except only a mass of gas reservoirs produce water. In order to ensure the accuracy of the study, the irreducible water saturation is defined

Fig. 3 Distribution frequency of skin factor obtained from the pressure recovery tests

reasonably in the model and the effect of the water production phenomenon simulated accurately. Here combining gas test data with logging data we get the logging water saturation, which is interpreted as dry layer in the gas test, is the irreducible water saturation of the reservoir. The regression results of a good deal of data between irreducible water saturation and permeability are shown in Fig. 4. The movable water saturation, which is interpreted as containing a small amount of water layer in the gas test, is the difference between the logging water saturation and the calculated irreducible water saturation by the regression relation.

Numerical simulation results

History matching

Make use of eclipse software to conduct numerical simulation. In the light of the above results to modify reservoir

Fig. 4 Regression relation curve between irreducible water saturation and permeability

parameters in the history matching, the prior modified parameters should be skin factor and permeability and then transmissibility. The modified scale of the skin factor, permeability, and transmissibility should refer to the microseismic monitoring data and pressure recovery test data.

Through the above process and analysis, the final history matching results are very good. The gas field and the single well production, including the cumulative gas production and the gas production rate, are completely matched. The

matching ratio of the gas field and the single well pressure is 92%. The results are shown in Fig. 5.

However, according to the real production situation, the present development well pattern is not reasonable. In order to get the reasonable development pattern, suppose that the sweet spot has no wells, then new wells should be designed and simulated again in this sweet spot. Finally, by comparing each scheme, the best development technology policy can be obtained and taken as reference for the same type reservoirs.

Demonstration of well type

Generally, the technical policy of development of tight gas reservoir takes horizontal wells as primary and vertical wells as secondary. According to the development research of this sweet spot, three cases are analyzed and designed: vertical well, horizontal well, and horizontal well combined with vertical well (Li et al. 2014; Ma et al. 2012). Within the effective range of this sweet spot, the three cases have designed the same parameter: the well space is 600 m with staggered well pattern, the length of the horizontal section is 1200 m, the initial production rate of the horizontal well is $8 \times 10^4 \text{ m}^3/\text{day}$, and the initial production rate of the vertical well is $2 \times 10^4 \text{ m}^3/\text{day}$. The simulation results are shown in Fig. 6.

As shown in Fig. 6, predicted for 30 years, the final gas field cumulative gas production of the three cases is nearly

Fig. 5 Numerical simulation results of the sweet spot

the same, but in the first 15 years, the gas field cumulative gas production of the vertical well, horizontal well, horizontal well combined with vertical well successively increases. The ground construction investment of this area is vast; the number of horizontal well is less than vertical well. At the same time, the increase in amplitude of gas field cumulative gas production between horizontal well and horizontal–vertical well is less, so it is recommended that the well type should use horizontal well. But vertical well can be designed in the area where it is difficult to deploy and implement horizontal well.

Demonstration of well pattern

The above demonstration results show that the development well type of tight gas reservoir should be horizontal well. Under this circumstance, design two cases (row well pattern and staggered well pattern) to demonstrate and optimize well pattern (Kuuskraa and Ammer 2004; Zou et al. 2013), shown in Fig. 7.

Within the effective range of this sweet spot, the 2 cases designed have the same parameter: the well space is 600 m, the length of the horizontal section is 1200 m, the initial production rate is $8 \times 10^4 \text{ m}^3/\text{day}$, and the number of designed wells is 14. The simulation results are shown in Fig. 8.

As shown in Fig. 8, predicted for 30 years, the final gas field cumulative gas production of the 2 cases are nearly same, but in the first 15 years, the gas production rate of the staggered well pattern is better than the row well pattern. Therefore, it is recommended that the horizontal well should use staggered well pattern by taking the horizontal well life and the minimum period of cost recovery into account.

Demonstration of well space

Base on the principle of horizontal well with staggered well pattern, 4 cases are designed (400, 600, 800, and 1000 m) to demonstrate and optimize well space (Wang et al. 2008;

Fig. 7 Sketch map of row well pattern and staggered well pattern

Zhu et al. 2012; Jia et al. 2010). In the effective range of this sweet spot, the 4 cases designed have the same parameters: the length of the horizontal section is 1200 m and the initial production rate is $8 \times 10^4 \text{ m}^3/\text{day}$. The number of designed wells in each case is 20, 14, 10, and 8, respectively. The simulation results are shown in Fig. 9.

As can be seen in Fig. 9, predicted for 30 years, the gas field cumulative gas production of the 1000, 800, 600, and 400 m successively increases, but the increase in amplitude becomes smaller and smaller. The final gas field cumulative gas production of the 400 m is nearly equal to 600 m, and the final gas field cumulative gas production of the 800 m is nearly equal to 600 and 400 m. Therefore, it is recommended that the horizontal well space should be 600–800 m.

According to the actual drilling and production condition of this sweet spot, so far 11 horizontal wells and 6 vertical wells have been drilled, and the well space is about 400–600 m. The final gas field cumulative gas production of the actual development well space is nearly equal to 600–800 m, which shows the actual development well space is too small for this sweet spot. Therefore, it is recommended that the horizontal well space should be 600–800 m.

Fig. 6 Demonstration of well type—the cumulative gas production curve of the sweet spot

Fig. 8 Demonstration of well pattern—the cumulative gas production curve of the sweet spot

Fig. 9 Demonstration of well space—the cumulative gas production curve of the sweet spot

Fig. 10 Demonstration of the length of the horizontal section—the cumulative gas production curve of the sweet spot

Demonstration of the length of the horizontal section

For the demonstration of the length of the horizontal section,

5 cases are analyzed and designed: 800, 1000, 1200, 1400, and 1600 m (Zeng et al. 2013). In the effective range of this sweet spot, the 5 cases designed have the same parameters: the horizontal well space is 600 m with staggered well pattern; the initial production rate is $8 \times 10^4 \text{ m}^3/\text{day}$; the number of designed wells is 14. The simulation results are shown in Fig. 10.

As can be seen in Fig. 10, predicted for 30 years, the cumulative gas production in gas field at the 800, 1000, 1200, 1400, and 1600 m successively increases. Therefore, according to the results of LWD, if the sand body drilling rate is high, the length of the horizontal section can be appropriately increased. But due to the limitation of the effective range, the actual drilling ability and the drilling cost, it is recommended that the length of the horizontal section should be 1200 m.

Demonstration of gas production rate

For the demonstration of gas production rate, 4 cases are analyzed and designed: 3×10^4 , 5×10^4 , 8×10^4 , $10 \times 10^4 \text{ m}^3/\text{day}$. In the effective range of this sweet spot, the 4 cases designed have the same parameters: the horizontal well space is 600 m with staggered well pattern; the length of the horizontal section is 1200 m; the number of designed wells is 14. The simulation results are shown in Fig. 11.

As shown in Fig. 11, predicted for 30 years, the gas field cumulative gas production of the 4 cases is slightly different. The gas field cumulative gas production of the $3 \times 10^4 \text{ m}^3/\text{day}$ case is significantly lower, and the gas field cumulative gas production of the other 3 cases is nearly same. But, for the gas field cumulative gas production of the first 15 years or for the stable production period of single well, with the increase of the initial gas production rate, the stable production period shortens and the decrease in amplitude becomes smaller and smaller. The gas field cumulative gas production of the first 15 years is increasing with the increase in

Fig. 11 Demonstration of gas production rate—the cumulative gas production curve and daily gas production curve of single well of the sweet spot

the initial gas production rate, but the increase in amplitude becomes smaller and smaller. The final gas field cumulative gas production of the $8 \times 10^4 \text{ m}^3/\text{day}$ is nearly equal to $10 \times 10^4 \text{ m}^3/\text{day}$. So, it is recommended that the initial gas production rate is $8 \times 10^4 \text{ m}^3/\text{day}$ by considering investment cost of building ground pipeline (Wang et al. 2014).

Conclusion

1. According to the results of microseismic monitoring and pressure recovery test, the corrected irreducible water saturation, reservoir parameters should be modified in history matching and the accuracy of history matching should be improved.
2. The sweet spot in tight gas reservoir should be developed by horizontal well with staggered well pattern, the well space is 600–800 m, the length of the horizontal section is 1200 m, and the initial gas production rate is $8 \times 10^4 \text{ m}^3/\text{day}$.

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Compliance with ethical standards

Conflict of interest The authors confirm that this article content has no conflict of interest.

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