Well-controlled area seepage law and disturbance degree between production wells prediction of tight gas reservoir: a case study of Sulige gas field, Ordos Basin, NW China

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Abstract

Based on a sum of well test interpretation analysis, the flowage characteristics of the gas in reservoir were analyzed from physical parameters and double-logarithm curve characteristics of gas wells. The result showed that the permeability of gas well-fracturing area is greatly improved, which is the main area to provide productivity. The speed of pressure transmission was slow because of extremely low permeability of outside the fracturing area and fluid flow was dominated by a linear flow. And three common well test interpretation models were extracted. The characteristics of bi-zonal compound reservoir of gas wells were specified by combination with peripheral supply and pressure change characteristics of gas wells. Variations of reservoir pressure and flowing bottom-hole pressure with time were simulated and quantified under different physical parameters and daily production. And the rational proration scheme of gas production wells was established by integration with numerical simulation method. Numerical simulation results of 21 sets of well patterns showed that there were two recovery inflection points. And a new model was built to research well interference degree that was defined by a new and original mathematical expression about production. The result showed that the infill well pattern should be controlled at $500\text{ m} \times (500\text{--}600)\text{ m}$.

Keywords Sulige · Dynamic analysis · Numerical simulation · Peripheral supply · Pressure change · Disturbance degree

Introduction

Since its establishment in 2002, the Sulige gas field has encountered unprecedented challenges and is considered a “world-class development problem.” The large area of “three lows”, low permeability, low porosity, and low saturation, strong heterogeneity, small effective sand body size, poor lateral continuity, small single-well control reserves, and rapid pressure drop make Sulige gas field development difficult to sustain (Li et al. 2010). Although the predecessors used a few years of experimental development to obtain the test, well test and production dynamic data, and carried a

lot of researches of development performance of the region, most of them did not combine the reservoir conditions with production dynamics of the I, II, III wells in the area with a quantified survey. Researchers summarized a set of methods applicable to the well test interpretation of the Box 8 gas reservoir through the analysis of the well test data, but did not summarize the main well test model, gas well physical properties, and boundary characteristics (Tian et al. 2013). He et al. (2012) obtained the optimal well spacing by evaluating the geological model, the venting radius, the interference test well, the numerical simulation, and the economic benefit. The shortage is that it did not establish a model to study the interference situation under different well spacing and quantify the degree of interference. In view of this, this paper comprehensively uses well testing, production instability analysis, and numerical simulation to quantitatively discuss and summarize the seepage characteristics, production dynamic characteristics, and well pattern optimization of gas well control areas in this area.

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Seepage characteristics of well-controlled area

The downhole test in the Sulige gas field is mainly based on pressure recovery and modified isochronous well testing. The analysis of the 60 well pressure recovery well testing and the 8 modified isochronous well testing data show that the seepage geometry of the main reservoir in this area is in linear flow, only three times show a late pseudo-radial flow stage, and there was not much local radial flow after the early linear flow section. In the aspect of the physical property parameters, if the probability accumulation curve (P_{20} – P_{80}) of each parameter taken as its main distribution interval, the effective permeability is mainly distributed in $(0.06\text{--}0.38) \times 10^{-3} \text{ } \mu\text{m}^2$, with an average of $0.21 \times 10^{-3} \text{ } \mu\text{m}^2$; the formation coefficient is $(0.50\text{--}6.34) \times 10^{-3} \text{ } \mu\text{m}^2 \text{ m}$, average is $2.71 \times 10^{-3} \text{ } \mu\text{m}^2 \text{ m}$; the half length of the crack is mainly distributed in $(25\text{--}90)\text{m}$, with an average of 67 m, belong to low permeability–extra low permeability type, big differences exist between wells, well completion and fracturing effect is good. Vertical cracks occur in the fracturing zone, and the effective permeability is high. The permeability outside the fracturing zone is low and the pressure conduction is slow, which is the main reason for the continuous existence of linear flow.

From the perspective of double-logarithmic curve, there are three types of gas reservoir models: homogeneous, composite, and double pores, each with 53, 10, and 5 wells, which proves that the Box 8 gas reservoirs in this area are mostly homogeneous and composite reservoirs. In the aspect of well models, the early pressure recovery curves all show a straight line with a slope of 1, after the transition, the pressure and its derivative curve rise parallel with a 1/4 slope (35 wells), and both the distance of the ordinate is 0.602 logarithmic period, which means that all wells have wellbore reservoir effect, and after the transition period and before the boundary effect, the fluid seepage is mostly bilinear flow perpendicular to the crack and flowing along the crack, and because the gas wells in the Sulige gas field need to be fractured before they can be put into production. Therefore, the well model is generally fixed reservoir & skin & crack limited diversion; in terms of boundary model, it is mainly parallel and rectangular closed boundary (respectively 29 and 14 wells), and this is mainly due to the deposition of rivers in the main layer box of the area, which is easy to form a strip-shaped blocking boundary (Bi et al. 2013), especially in the floodplain area of between rivers.

In summary, the well test interpretation models of gas wells in this area are mainly the following three types: fixed well storage & skin & fracture limited diversion & homogeneous reservoir & parallel boundary (Fig. 1a); fixed well storage & epidermis & crack limited diversion &

Fig. 1 The four types of the double-logarithmic curve of the Su X block in the Sulige gas field

homogeneous reservoir & rectangular boundary (Fig. 1b); fixed well storage & skin & radial composite & infinite boundary (Fig. 1c). In addition, very few wells also have the situation of “fixed well storage & epidermis & homogeneous reservoir & parallel boundary” in the study area (Fig. 1d). Because the number of wells is small and not universal, no further study is conducted here. The common double-logarithmic curve of the Su X block in the Sulige gas field is shown in Fig. 1. It can be used as a comparison in the subsequent interpretation work.

Production dynamic characteristics

Gas well peripheral recharge characteristics

The typical gas well pressure drop curve in this area shows a strong peripheral recharge effect. The P/Z - G_p curve is rapidly upturned after a short linear fall, and the different straight line segments are extrapolated to correspond to the reserves of different physical gas layers. Zone I reflects the dynamic reserves controlled by the high-permeability medium gas layer with good physical properties in the reconstructed area, and Zone II is the dynamic reserve controlled by the peripheral long well recharge area. In order to quantify the range of gas well hyperosmotic medium and its controlled dynamic reserves, the average pressure flow curve of a total of 16 production wells in 2002 was selected and analyzed (Fig. 2).

It can be seen from the figure that the average casing pressure in the first 10 months is approximate linear drop, roughly corresponding to the I zone of the typical P/Z - G_p

pressure drop curve; the production of this period is in accordance with the exponential decreasing law. According to the regression index above, the average single-well-accumulated gas volume under the 16 wells high-permeability medium system is about $495 \times 10^4 \text{ m}^3$. By comparison, dynamic reserve of the area of the high permeability is calculated by the material balance equation of the two-zone composite reservoir (Wang et al. 2004), the average value of 14 wells is $715 \times 10^4 \text{ m}^3$, and the average reserve abundance is $1.36 \times 10^8 \text{ m}^3/\text{km}^2$. Calculated by circular boundary, under the radius 108–133 m, belong to high-permeability medium area, roughly 1.6 to 2 times of the reconstructed area.

In addition, the statistical results of the pressure drop of the 211 production wells show that the average set pressure drop gas production of Class I, II, and III wells is 182, 101, $50.8 \times 10^4 \text{ m}^3/\text{Mpa}$, respectively. The linear regression yields the relationship between the gas pressure and the cumulative gas production (Fig. 3a). The slope of 18.19 is the average pressure drop of these gas wells. The formula between the cumulative gas production and the pressure drop is obtained by the regression. (Figure 3b), according to the figure: When the gas well production is only $(500\text{--}600) \times 10^4 \text{ m}^3$, the casing pressure has dropped (15.5–16.0) Mpa, and it enters the low-pressure production period; the pressure of the inflection point drop is about 16 Mpa, means that the gas wells are produced below 7 Mpa for a long time; at present, the total amount of gas at this batch of gas wells is $1952 \times 10^4 \text{ m}^3$, and the proportion of gas produced during the high-pressure period is less than 30%. It can be seen that the high-pressure production period of the gas well roughly corresponds to the high-permeability medium, while the peripheral recharge is in the low-pressure production period; there must be a

Fig. 2 The average pressure flow curve of a total of 16 production wells in 2002

Fig. 3 The linear regression yields the relationship between the gas pressure and the cumulative gas production & the cumulative gas production and the pressure drop

large difference of the effective permeability between the near-well and peripheral areas of the gas well, so that the pressure of initial/hyperosmotic medium system drops so rapidly; the total gas production in the peripheral recharge area is superior to the near well area, so an effective way of increasing the gas production and gas collection in a single well is to reduce the economic limit production and increase the recovery rate of the peripheral recharge area (Zhang et al. 2009).

Gas well pressure variation characteristics

Like most low-permeability heterogeneous gas reservoirs, since formation pressure is mainly related to cumulative gas production and well-controlled reserves, the formation pressure of the gas wells in this area is relatively flat, while the bottom-hole pressure is due to the distribution, physical properties, and flow-blocking boundaries drop rapidly and fluctuate intensively, causing the imbalance and unsynchronous of imbalance of the two pressures (Wang et al. 2014). The II and III gas wells are often intermittently produced, and the stability and productivity of gas wells are weak. In order to quantify the changes of formation pressure and bottom-hole flow pressure under the influence of the

above factors, reveal the general characteristics of various gas well pressure drops, provide guidance for the production, three simulation wells corresponding to the reservoir and production characteristics of class I, II and III wells are established, which are simulated and analyzed by using the related technologies of well test and production instability analysis. Specifically, the average reservoir coefficient values of the I, II, and III wells in the area are assigned to the three simulated wells firstly; then according to Class I, II and III, they are assigned to the discharge area and well control of the three simulated wells. Finally, under the consistency of other parameters, the initial pressure is set to the average formation pressure (about 29.5 Mpa). The pressure of three gas wells under different effective permeability, daily output and crack half length is simulated by univariate simulation (Zhou and Tang 2007). The simulation parameters are designed as shown in Table 1. When simulating a variable, other variables are averaged (the bold value in the table) and end with the flow pressure drops to 2 Mpa.

The simulation results show that the effective permeability K and the daily output Q have the greatest impact on the pressure drop imbalance; when K is greater than $0.1 \times 10^{-3} \mu\text{m}^2$, the I, II and III wells can be stably produced for more than 2 years under their respective production

Table 1 Table of the simulation parameters of class I, II, III wells

Well classification	Simulation parameters				
	Effective permeability $K/10^{-3} \mu\text{m}^2$	Crack half length X_f/m	Daily output $Q/10^4 \text{m}^3$	Average discharge/ km^2	Well-controlled reserves/ 10^4m^3
Class I wells	0.05/0.1/ 0.2 /0.4	30/45/65/ 80	1/2/3/4	0.33	4500
Class II wells	0.05/ 0.1 /0.2	30/45/ 65 /80	1/2/3	0.18	2500
Class III wells	0.05 /0.1/0.2	10/30/ 45 /65/80	0.5 /1	0.11	1500

(Fig. 4a–c). Because the effective permeability (obtained through well test interpretation) of the most gas wells is less than $0.1 \times 10^{-3} \text{ um}^2$, the production allocation of these wells cannot exceed $2 \times 10^4 \text{ m}^3/\text{d}$. However, if the effective permeability is greater than $0.1 \times 10^{-3} \text{ um}^2$ and the well control reserves are more than $4500 \times 10^4 \text{ m}^3$, the gas well production allocation can be increased to $2 \times 10^4 \text{ m}^3/\text{d}$ (Fig. 4a, b); each influencing factor has a compensatory or growth effect, and the crack half length (X_f) has a strong influence on the class III well (Fig. 4c). The permeability of Class I wells is relatively high, and the influence of crack length is small. Under the corresponding to average reservoir parameters and production, the pressure drops is slow, and the rate of declining is: $\text{I} > \text{II} > \text{III}$ (Fig. 4d); the inflection point of the effective penetration rate, daily output, and the half length of the crack are $0.1 \times 10^{-3} \text{ um}^2$, $2 \times 10^4 \text{ m}^3/\text{d}$, and 30 m respectively. After the inflection point, the life of the gas well is greatly increasing.

Based on this, according to the stable production strategy of Sulige gas field (Wu et al. 2007; Lu et al. 2015; Zuo et al. 2015), the production series of I, II, and III wells

were simulated by the 2-year and 3-year stable production period, and the average predictable gas production curve of the three types of gas wells were obtained after comparison. The results show that Class I wells can be produced with $1.5\text{--}2.0 \times 10^4 \text{ m}^3/\text{d}$, their lifespan is 14 years, the accumulated gas can reach $3400 \times 10^4 \text{ m}^3$. Class II wells can be produced with $0.9\text{--}1.2 \times 10^4 \text{ m}^3/\text{d}$, their lifespan is 10 years, and the accumulated gas is about $1750 \times 10^4 \text{ m}^3$; the class III wells can be produced with $0.5\text{--}0.6 \times 10^4 \text{ m}^3/\text{d}$, their lifespan is 8 years, and the accumulated gas is about $850 \times 10^4 \text{ m}^3$. The final cumulative gas production of gas wells is almost unaffected by the stable production time.

Gas well production flow characteristics

In the case of composite zone, the gas well is in an unstable flow state for a long time, and the dynamic reserves calculated under the transient effect changed dynamically with time, and it is difficult to grasp the final dynamic reserve of the gas well (Luo et al. 2010; Alkough et al. 2014). In the literature 11, by tracking the production of typical gas wells

Fig. 4 Dynamic prediction of formation pressure and BHP under different physical parameters and daily production configuration

in the Su X block for many years, using the RTA software calculate the dynamic reserves at different times, and the prediction plates were established. The results show that the time of the well-controlled dynamic reserves before it was put into production is about 3.5 years. However, when it was applied to this reserve, it was found that some wells flow extremely slow in production, the reserves are small, and the growth of reserves was easily ignored due to poor peripheral properties (Mattar and Anderson 2003; Zhang 2010). The Su Y encryption zone is the best physical region in the middle of Sulige, based on some gas wells (more than 7 years) and the current dynamic reserve bubble map (Fig. 5).

Conclusion that the dynamic reserves are growing, and in other areas with poorer physical properties, the “time-delay effect” is more profound can be drawn. In view of this, after using the Agarwal–Gardner flow material balance method and the production data fitting method, calculating the dynamic reserves of each time node, and classifying and averaging the time found that: Class I and II wells before it was put into operation about 5 years needed and they can seep to the recharge boundary; Class III can reach 80% of the final reserve after 4 years of production (Deng et al. 2013).

Reasonable development of well network

Well network research

In view of the fact that the effective sand body of the facies reservoir is controlled by lithology, the well points of the

uniform well network cannot be guaranteed located in the effective sand body. Therefore, the designed well spacing (300–800 × (300–800) m 21 sets of regular well patterns were set with a lower limit of 2 m of effective thickness, and filtering the well pattern and eliminating invalid well points (Table 2).

The simulative results show that there is an inflection point (0.4 km^2 , $2000 \times 10^4 \text{ m}^3$) exist between the single-well gas production and well-controlled area, when the well-controlled area continues to increase, the cumulative gas production drop gradually; when the well-controlled area under about 0.3 km^2 , the production is greatly slow down, indicating that the degree of disturbance is greatly increased. There are two inflection point exist the well network schemes of oil recovery rate (scheme 12, scheme 16), namely $500 \times 500 \text{ m}$ and $600 \times 700 \text{ m}$. The recovery rate is 50.75% and 39.1%, respectively (Fig. 6). In the steep slope area, the recovery rate decreases rapidly with the increase of the well pattern, and the variation range is large. The recovery rate of the gentle slope area is decreasing with the continuous encryption of the well pattern, and therefore, excessive encryption does not always bring economic benefits. In view of this, it is wise that to select an intermediate transition zone with a well spacing of 500 m.

Degree of interference study

Based on the survey of the well pattern scheme, established a model to simulate the pressure of the interwell, studied the interference situation under different well

Fig. 5 The current dynamic reserve bubble map of encryption zone in the middle of Sulige

Table 2 Different well pattern density schemes

Number	Well spacing (m)	Row spacing (m)	Well number	Effective number of Wells	Number	Well spacing (m)	Row spacing (m)	Well number	Effective number of Wells
Scheme 1	300	300	329	274	Scheme 12	500	500	121	104
Scheme 2	300	400	248	207	Scheme 13	500	600	102	88
Scheme 3	300	500	193	161	Scheme 14	500	700	87	75
Scheme 4	300	600	165	138	Scheme 15	500	800	76	66
Scheme 5	300	700	143	120	Scheme 16	600	600	89	77
Scheme 6	300	800	134	113	Scheme 17	600	700	73	64
Scheme 7	400	400	196	166	Scheme 18	600	800	63	55
Scheme 8	400	500	156	132	Scheme 19	700	700	54	47
Scheme 9	400	600	130	111	Scheme 20	700	800	45	40
Scheme 10	400	700	109	93	Scheme 21	800	800	40	35
Scheme 11	400	800	95	81	–	–	–	–	–

Fig. 6 Effect diagram of well pattern scheme prediction

spacing, and quantified the degree of interference by gas production. The specific process as follows: Firstly, the average discharge area of the gas well in the area was assigned to all the simulated wells to ensure that the well pattern schemes are comparable; then the simulated wells are separately opened for production with enough time, and the arithmetic of the accumulated gas is taken. The average value is recorded as Q_0 . Finally, under the guarantee of sufficient row spacing, simulating the production by different wells spacing, and then under the guarantee of enough wells spacing, simulating the production by different rows spacing, obtained the accumulated gas production of different simulated wells, recorded as Q_i , the degree of interference of gas production of a single well

can be characterized by the following mathematical formula (Wang et al. 2015):

$$P_w = 1 - \frac{Q_i}{Q_0} \quad (1)$$

According to the formula 1, the interference degree of well pattern can be calculated from the interference degree of gas production of single well:

$$P_p = 1 - \frac{1}{nQ_0} \sum_{i=1}^n Q_i \quad (2)$$

P_w is the degree of interference of a single well; P_p is the degree of interference of the well pattern; n is the total number of wells.

Using formula 2 to calculate the simulation results, it can be obtained the interference degree curve of the quantified average accumulated gas production of the single well. From this curve, under the current geological conditions, the interference degree of the row spacing direction is higher than the well spacing direction; when the row spacing is less than 500 m, the degree of interference increases sharply; the interference degree of using a $500 \times (500\text{--}600)$ m well pattern is less than 20% (Fig. 7).

In addition, from a row spacing of 700 m, and the simulated pressure distribution plan of a well spacing changed from 500 m to 600 m, it can be seen that when the well spacing is greater than 500 m, the interference of interwell is greatly reduced, while the row spacing is increased to 700 m above, there is almost no interference in the direction of the sand body (Fig. 8). In fact, it is also found in the daily production instability analysis that only when the well spacing is less than 600 m, the data points of the mid-late stage of Blasingame characteristic curve appear downward, proving that there is interference.

In summary, considering that gas wells need at least $1350 \times 10^4 \text{ m}^3$ of gas production in this area and the cost can be recovered. It is recommended that when the well network is encrypted, the well spacing should be controlled at 500 m, and the row spacing should be controlled at 500–600 m (reasonable recommendation 550 m). In this way, it can maintain a high degree of well control and a recovery rate, while maintaining the interference less than 0.2, thus ensuring the economic benefits of a single well.

Conclusions

1. Overall, the gas wells have the characteristics of “two-zone composite reservoir” in this area. Although the underground operation has achieved the purpose of

Fig. 8 Simulated pressure distribution plan

- improving the reservoir of surrounding wells, the scope is limited, and the permeability of the reservoir outside the gas well is greatly reduced, resulting pressure conducted is slow, the well-controlled reservoir area generally flows linearly with multiple choke boundaries.
2. Due to the effective permeability, there exists a large difference between the near well zone and the peripheral zone, the initial pressure of the gas well decreases rapidly, the downhole flow pressure and the formation pressure drop are not synchronized, and the gas well is in an unstable flow state for a long time, maintained in the low-pressure and low-yield by peripheral recharge, although the physical properties of the peripheral recharge zone are poor, but its total gas production is superior.
3. In order to ensure wells of higher recovery rate and controlled degree, lower interference level, improving single-well benefits, the post-well network encryption should be controlled at $500 \text{ m} \times (500\text{--}600) \text{ m}$.

Fig. 7 Interference degree prediction results

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