Study on Well Spacing Optimization in a Tight Sandstone Gas Reservoir Based on Dynamic Analysis

Xiaoxu Feng* and Xinwei Liao*

ABSTRACT: Compared to the shale gas and coalbed methane in China, tight gas has been recently considered as a priority in the exploration and exploitation of unconventional gas resources. In the development of a tight gas field, how to enhance the gas recovery is a prevalent topic. Unlike the conventional gas reservoir, the ultimate gas recovery is not only determined by the geological characteristics but is also affected by other factors such as well drainage area and well spacing design. For tight sandstone reservoirs, the gas recovery can be improved by increasing the drainage area. Moreover, the well drainage area is closely associated with well spacing. Therefore, effective drainage area estimation and well spacing optimization are essential aspects for tight gas exploitation. In this paper, a new optimization workflow is established, which combined dynamic analysis and numerical simulation techniques. First, through interference well test results and production data dynamic analysis, the total gas production can be expressed and predicted. Then the well density can be optimized by the economic evaluation method. Meanwhile, a numerical model is built up to determine the optimal well spacing. This new optimization workflow can provide guidance to the operators of tight gas fields where the interference well test results are available and several years of production data are collected. Furthermore, in the case of the Sulige gas field, the single well drainage area is estimated and the optimal well pattern is obtained by the established approach. The results indicate that the well pattern of 500 m × 600 m is most reasonable for the pilot gas field.

1. INTRODUCTION

In the world energy market, the consumption of natural gas is progressively increasing. In 2018, natural gas had a remarkable increase of 4.6% in consumption and 5.2% in production due to the U.S. shale revolution. Even some projections point out that natural gas consumption will surpass oil and coal resources, topping the list of fossil fuel energy by 2030.1–4 This upcoming change meets the common demands for environmentally friendly and sustainable development all around the world. In recent years, unconventional gas including tight gas, shale gas, and coalbed methane plays a more and more important role in world energy supply. In China, the production of tight gas exceeded 343 × 10^8 m^3, contributing 23.2% of the total natural gas output of 1480.3 × 10^8 m^3 in 2017.1–4 Currently, tight gas is probably the most promising clean energy resource in China.

There are many difficulties and challenges in the development process,5 such as low permeability and small drainage area, which result in low gas recovery. For low permeability formations, the ultimate gas recovery is strongly associated with well drainage area, which is dominated by the well placing design. Meanwhile, the estimation of effective drainage area is the basis for well spacing optimization. The estimation methods of effective drainage area with dynamic analysis include material balance equation, type curve analysis, and other production analysis.6 The RTA analysis method through the log–log type curve is applied in this article to evaluate the single well controlled area by a current well pattern. With the understanding of single well controlled area, the optimization result of the well pattern can be more accurate. At present, the optimization methods of the well pattern for tight gas reservoirs mainly include the geostatistical method,7,8 production potential method,9,10 gas reservoir mathematical method,11–13 and numerical simulation method.14 He et al. optimized the well spacing and well array by the numerical simulation method, which takes the geological complexity into consideration. Then they regarded the interference well test results as a verification of the numerical simulation optimization method.14 They focused on numerical calculation but failed to make full use of the interference well test data and production data. Onwunalu and Durlofsky12,13 proposed a new well pattern optimization...
method by introducing a new well pattern description and combined it with a particle-swarm optimization technique. They accomplished the optimization by transforming the optimizing object from the well pattern itself into parameters associated with the well pattern. They completed a perfect work in well pattern type and well pattern geometry determination. However, the connectivity between wells is not involved. Therefore, a thorough approach of well spacing determination for tight gas is urgently needed.

2. THEORY

The determination of a reasonable well pattern depends on dynamic analysis and numerical simulation methods. Rate transient analysis, interference well testing, and statistical analysis contribute to the estimation of drainage area and ultimate recovery used to optimize the well density, as shown in Figure 1. Meanwhile, the commonly used numerical method can serve as a verification of the dynamic method and can help determine the optimal well spacing and well array.

2.1. Overview of the Target Pilot Field.

The Sulige gas field, a typical tight sandstone gas reservoir in China, is located in the Ordos basin where the depositional environment was pericontinental marine during the early Ordovician to early Paleozoic. It was first discovered in 2001 and has been explored and developed since 2006. The target pilot gas field is located in the southern part of the Sulige gas field with 67.6 km² in area. The exploration of the block began in 2008, and well logging and core sample investigation reveal that the average net pay thickness is about 10.7 m around the pilot gas field. Through core sample analysis, it shows that the porosity ranges from 3 to 13% and the average value is 7.9%. The permeability ranges from 0.006 to 0.680 md, and the average value is 0.108 md.

Figure 1. Research idea of the optimization.

Figure 2. Drainage area estimation by log–log type curve (Well S1).
2.2. Effective Drainage Area Estimation. For the conventional gas reservoir, the ultimate recovery is determined by the geological characteristics of the reservoir itself when depletion exploitation is applied, while for the unconventional gas reservoir, it is a different situation. Because of the extremely low permeability and complex pore throat structure, the single well drainage area is far smaller than the ideal reservoir. That is why the drainage area becomes a key factor that affects the ultimate gas recovery. Decline curve analysis, material balance equation, and production analysis are widely used to estimate the drainage of a tight gas well. Gas production analysis is a type curve matching technique used in formation property interpretation.

According to the type curve analysis theories, the maximum volume for fluid production can be calculated when the boundary flow (pseudo-steady state, PSS) is detected by the advent of a unit slope straight line on a diagnostic log-log or Blasingame plot. In other words, the single well drainage area can be estimated with the observation of a straight line on a log-log plot of rate normalized pressure integral (divided by equivalent time) and its derivative versus equivalent time. As shown in Figure 2, the single well drainage area of Well S1 can be obtained by commercial software, which is 0.35 km².

In the target block, production data of 56 wells are gathered to calculate the current single well drainage area using PPS flow regime recognition. Most of these wells can provide more than 5 years production data. The estimated results are shown in Figure 3. It indicates that, after more than 5 years of development, the average single well drainage area is 0.25 km² currently, and more than 90% of the 56 wells’ drainage areas are less than 0.4 km².

2.3. Interference Well Testing Analysis. In order to make a better understanding of the connectivity of the Sulige gas field, extensive interference well testing was performed with pressure measuring equipment installed at the bottom of the selected wells. After well testing interpreting, the interference probability \( F \) can be defined as the ratio between the amount of interfering wells \( n_i \) and total wells \( n_{total} \)

\[
F = \frac{n_i}{n_{total}} \tag{1}
\]

Based on the statistical analysis of interference well testing results, the relationship between interference probability and well density can be obtained. There is a relatively good relationship between well density and interference probability, as shown in Figure 4. Then the relationship can be expressed as eq 2.

\[
F = -0.0062x^3 + 0.0756x^2 - 0.0529x - 0.2286 \\
(2.5 \leq x \leq 7.5) \tag{2}
\]

2.4. Gas Well Production Estimation. The total gas production equals the sum of production of interfering wells and noninterfering wells. A noninterfering well can be treated as one single well in a tiny independent depletion reservoir. On the other hand, the interfering wells can be regarded as multwells producing in one closed gas reservoir since they are interconnected to some extent.

2.4.1. Production of a Noninterfering Well. As wells in the pilot site are mostly producing under a constant pressure, the Arps decline curves can be applied. According to Arps laws, when \( n = 0.5 \)

\[
q = \frac{q_i}{(1 + 0.5Dt)^2}. \tag{3}
\]

Then the single well cumulative gas production can be expressed as follows

\[
G_{qf} = \int_0^t q dt = \frac{2q_i}{D_i} \left[ 1 - \left( \frac{q_{i}}{q} \right)^{1/2} \right] \tag{4}
\]

By setting \( a = \frac{0.5D_i}{q_i} \) and \( b = \frac{1}{q} \), eq 4 can be transformed into

\[
G_{qf} = \frac{t}{at + b} \tag{5}
\]

Through matching the production data of noninterfering wells in Sulige, the values of \( D_i \) and \( q_i \) can be determined. Then the cumulative production of a single noninterfering well can be estimated by eq 6.

\[
G_{qf} = \frac{t}{0.000281t + 0.002202} \tag{6}
\]
where \( t \) is the production time, year; and \( G_{sf} \) is the single well cumulative production of interfering well, \( 10^4 \text{ m}^3 \).

2.4.2. Production of the Noninterfering Well. Researchers found that there was a good polynomial regression relationship between well density and the production ratio of interfering well to noninterfering well,\(^{15} \) as shown in Figure 5. In this way, the production of interfering wells can be expressed as a function of well density.

![Figure 5. Statistical relationship between \( G_f/G_{sf} \) and well density.](image)

\[
\frac{G_f}{G_{sf}} = -6.1993s^4 + 0.0121s^3 - 0.0739s^2 + 0.0516s + 0.9864 (1 \leq s \leq 7.5)
\]  
(7)

where \( G_f \) is the single well cumulative production of interfering well, \( 10^4 \text{ m}^3 \); and \( s \) is the well density, wells/km\(^2\).

2.4.3. Gas Recovery Estimation. For a tight gas field with interference well testing results, the gas well production can be calculated through interference probability and well density. Then the optimization method can be applied regarding the overall profit and ultimate gas recovery as objective indicators to determine the optimal well density.

According to the definition of gas recovery, the ultimate gas recovery can be given by

\[
R = \frac{G}{N} = \frac{A[sG_f(1 - F) + G_{sf}F]}{AB}
\]  
(8)

where \( G \) is accumulative gas production, \( 10^4 \text{ m}^3 \); \( R \) is ultimate gas recovery, \%; \( N \) is gas volume initially in place, \( 10^4 \text{ m}^3 \); \( A \) is reservoir area, \( \text{km}^2 \); and \( B \) is reserve abundance, \( 10^4 \text{ m}^3/\text{km}^2 \).

2.5. Optimization by Economic Indicator and Gas Recovery. According to the results of drainage area estimation and the well patterns commonly used in the Sulige gas field, eight typical well patterns were designed for economic evaluation analysis, as shown in Table 1. As mentioned before, the current single well drainage area is about 0.25 km\(^2\). Meanwhile, among these eight groups, there are two groups where single well controlled area is smaller than the current single well drainage area, two groups that are close to the current value, and four groups that are larger than 0.3 km\(^2\).

![Table 1. Well Pattern Design for Economic Evaluation](image)

| parameter               | value |
|-------------------------|-------|
| area A                  | km\(^2\) | 67.6 |
| reservoir abundance B   | \(10^4 \text{ m}^3/\text{km}^2\) | 14,800 |
| commodity rate V        | decimal | 0.96 |
| taxes W                 | yuan/\(10^4 \text{ m}^3\) | 1300 |
| single well investment b| yuan/\(10^4 \text{ m}^3\) | 85 |
| natural gas price P     | yuan/\(10^4 \text{ m}^3\) | 12,000 |
| operating cost C        | yuan/\(10^4 \text{ m}^3\) | 5000 |
| time                    | year   | 20   |

Then based on the relevant parameters recommended by “Economic Evaluation Parameters and Methods of Construction Project of China National Petroleum Corporation” (Table 2), an optimization method of well density can be built up.

![Table 2. Reference Values for Profit Calculation](image)

| parameter               | unit     | value |
|-------------------------|----------|-------|
| area A                  | km\(^2\) |       |
| reservoir abundance B   | \(10^4 \text{ m}^3/\text{km}^2\) |       |
| commodity rate V        | decimal  |       |
| taxes W                 | yuan/\(10^4 \text{ m}^3\) |       |
| single well investment b| yuan/\(10^4 \text{ m}^3\) |       |
| natural gas price P     | yuan/\(10^4 \text{ m}^3\) |       |
| operating cost C        | yuan/\(10^4 \text{ m}^3\) |       |
| time                    | year     |       |

The profit of gas production equals total sales income minus total expenditure. Meanwhile, total sales income equals total gas volume multiply by gas price, and total expenditure equals investment cost plus operating cost and taxes. Then the total gas production can be given by

\[
G = G_fAsF + G_{sf}As(1 - F) = As[G_f + G_{sf}(1 - F)]
\]  
(9)

So, the profit can be obtained

\[
Pf = As[G_f + G_{sf}(1 - F)] \times (P - C - W) - Ab
\]  
(10)

where \( A \) is reservoir area, \( \text{km}^2 \); \( s \) is well density, wells/km\(^2\); \( V \) is commodity rate, decimal; \( P \) is the natural gas price, yuan/\(10^4 \text{ m}^3\); \( b \) is the investment cost, 10\(^4 \) yuan/well; \( C \) is the operating cost, yuan/\(10^4 \text{ m}^3\); \( W \) is the taxes, yuan/\(10^4 \text{ m}^3\); \( F \) is the interference probability, \%; and \( Pf \) is the profit, \( 10^4 \) yuan.

Then, when \( Pf = 0 \), the economic limit well density is obtained, while the absolute maximum value of \( Pf \) is the optimal profit when \( s \) is between 0 and 8. The corresponding \( s \) is the optimal well density. Based on the values in Table 2, the economic limit well density is 5.8 and the optimal well density is 3.2.

Then the curve of profit and well density and the curve of gas recovery versus well density are drawn in the same graph, as shown in Figure 6. Through observing the two curves, they both have inflection points. For the profit curve, when well density is lower than 3.2, the profit value shows an upward trend. However, when passing the inflection point, the profit tends to decrease gradually. Meanwhile, for the gas recovery curve, when well density is lower than 3.2, the recovery value increases.

![Figure 6. Well density optimization results with profit and gas recovery.](image)
rapidly. On the other hand, when well density exceeds the inflection point, the upward trend turns flatter. Therefore, both evaluation indicators show that the inflection point is the optimal well density for the target gas field block. The corresponding optimal well pattern is 500 m × 600 m.

2.6. Numerical Simulation. 2.6.1. Reservoir Geological Modeling. Reservoir modeling was conducted by combining a sedimentological study, sequence stratigraphic analysis, geostatistical simulations, and production data analysis. Former research revealed that the Ordos basin during the Upper Permian and Lower Triassic was a braided channel. The reservoir commonly consists of small ribbon channel deposits interbedded with mudstones.
The numerical model was scaled up with a grid interval of 100 m in vertical and 100 m in horizontal. The reservoir is described by 90 × 76 grids in horizontal and 2 lays in vertical, that is, 13,680 grids in total. In addition, according to the fracture half-length obtained from production dynamic analysis, local grid refinement is applied to ensure the accuracy of reservoir characterization. The number of local refinement grids of 67 wells is 864. Then the total amount of numerical grids is 14,544. The static parameters, reservoir fluids, rock parameters, and historical data provided by the geological model were imported into the numerical model (Figure 7). In order to provide a correct model for the coming predictions, the numerical model was modified by history matching including reserve matching and production history matching as shown in Figures 8 and 9.

Based on the reservoir numerical model, 14 simulation cases are designed with different well spacings and well arrays, as shown in Table 3. The optimization is implemented by comparing the single well cumulative production of each simulation case. Specifically, the well spacing ranges from 400 to 1000 m and well array ranges from 500 to 1000 m, then the single well cumulative production is simulated for further comparison. First, the well array with constant well spacing is changed to determine the optimal well array. Second, the well spacing with a fixed optimal well array is changed to determine the well spacing.

The simulation results show that the single well cumulative gas volume (well spacing 500 m) increases as the well array increases. However, there is a special point at 600 m (Figure 10), from where the slope of the curve turns lower. Therefore, 600 m should be considered as the optimal well array. In the same way, 500 m should be the optimal well spacing (Figure 11).

### 3. RESULTS AND DISCUSSION

1. Generally, the advent of the PSS flow regime signifies the emergence of boundary flow. Through flow regime production analysis and interference well tests, the drainage areas of 56 wells in the Sulige pilot site are evaluated. The results show that 90% of these 56 wells’ drainage areas are less than 0.4 km² and the average value of drainage area is 0.25 km².

2. Optimization with two indicators—profit and gas recovery—shows that the optimal well density is 3.2 wells/km². Compared with the drainage area estimated by

![Figure 9. History matching of daily gas production.](image-url)

![Figure 10. Well array optimization (well spacing = 500).](image-url)

**Table 3. Well Spacing Design for Numerical Simulation**

| well array/m | 500 | 600 | 800 | 1000 |
|--------------|-----|-----|-----|------|
| well spacing/m | 500 | 600 | 800 | 1000 |
| 400 | 500 | 600 | 800 | 400 |
| 400 | 500 | 600 | 400 | 400 |
trend. A numerical simulation result reveals that, for more than 5 years of exploitation, the average value of production increases from 500 to 1000 m. Meanwhile, the upward trend turns flatter at 600 m, illustrating that 600 m is the optimal well array. In the same manner, the optimal well spacing 500 m can be determined as well.

4. The numerical simulation optimization can be regarded as an independent method, but it is also a verification of the aforementioned well density optimization method. Results show that the two methods are consistent. Generally, the dynamic analysis optimization method is an alternative approach to help determine the optimal well spacing when the geological situation is not accurate enough to make the production forecast but the production dynamic data is available.

4. CONCLUSIONS

Drainage area of the tight gas well is closely related to the ultimate gas recovery. It is an important index throughout the gas field development process. In this paper, the drainage areas of 56 wells in the Sulige basin are evaluated through the production dynamic analysis method. The result shows that, after more than 5 years of exploitation, the average value of current drainage area is 0.25 km². This provides an important reference for the subsequent well spacing optimization. It indicates that the reasonable single well controlled area of well pattern design should be more than 0.25 km²; otherwise, well interference might happen more often.

In addition, an approach to optimize well spacing in tight gas is presented through engineering dynamic analysis and numerical simulation methods in this article. It involves production decline analysis, statistical analysis, and interference well testing interpretation. The results indicate that a well pattern of 500 m × 600 m should be the optimal scenario. The optimization method established can be used to help determine well pattern design both for the new gas reservoir and mature gas field with interference well testing data. Meanwhile, with the development of tight gas fields, more production data can be collected to estimate well drainage area more accurately. This can help to improve the well pattern design for a higher gas recovery.

Figure 11. Well spacing optimization (well array = 1000).

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