Research Article

Effect of Geological Heterogeneity on the Production Performance of a Multifractured Horizontal Well in Tight Gas Reservoirs

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Multifractured horizontal wells are widely used in the development of tight gas reservoirs to improve the gas production and the ultimate reservoir recovery. Based on the heterogeneity characteristics of the tight gas reservoir, the homogeneous scheme and four typical heterogeneous schemes were established to simulate the production of a multifractured horizontal well. The seepage characteristics and production performance of different schemes were compared and analyzed in detail by the analysis of streamline distribution, pressure distribution, and production data. In addition, the effects of reservoir permeability level, length of horizontal well, and fracture half-length on the gas reservoir recovery were discussed. Results show that the reservoir permeability of the unfractured areas, which are located at both ends of the multifractured horizontal well, determines the seepage ability of the reservoir matrix, showing a significant impact on the long-term gas production. High reservoir permeability level, long horizontal well length, and long fracture half-length can mitigate the negative influence of heterogeneity on the gas production. Our research can provide some guidance for the layout of multifractured horizontal wells and fracturing design in heterogeneous tight gas reservoirs.

1. Introduction

At present, hydraulic fracturing and horizontal well technologies, which are conducive to improving the well production and the ultimate recovery, are widely used in the development of unconventional low-permeable oil and gas reservoirs [1–4]. For hydraulic fracturing, the optimization of fracturing parameters has been paid extensive attention to improve the production of oil and gas wells [3–5]. The fractured well production performance can be promoted by optimizing the perforation clusters, cluster spacing, variable-rate fracturing, proppant size, and sand volume [5].

Thanks to the combination of the advantages of fracturing technology and horizontal well technology, multifractured horizontal wells have become the main development technology in many blocks. Issues concerning the transient flow of multifractured horizontal wells are always a hot spot for researchers [6–11]. Horne and Temeng [6] studied the transient flow of multifractured horizontal wells in infinite or confined reservoirs. Considering the fracture interference in the model, the seepage of the multifractured horizontal well can be divided into four stages, including the first linear flow, the first radial flow, the second linear flow, and the second radial flow. Zerzar et al. [9] introduced anisotropy into the transient pressure analysis of multifractured horizontal wells. The fluid flow in a multifractured horizontal well with finite conductive fractures can be divided into first linear flow, early radial flow, biradial flow, and pseudoradial flow. Wu et al. [10] established a comprehensive flow model of a multistage fractured horizontal well to study the effects of non-Darcy flow and stress sensitivity on the transient pressure response. Considering the effect of reservoir damage...
and fracturing fluid injection, a multistage fractured horizontal well model was built [11].

In fact, low-permeable tight oil and gas reservoirs have strong geological heterogeneity. Based on the classic homogeneous reservoir seepage theory, many researches extended it to the study of heterogeneous oil and gas reservoirs by analytical and semianalytical methods [12–18]. Pecher and Stanislav [12] proposed a method to investigate the transient behavior of heterogeneous reservoirs by the use of the boundary element method. Wolfsteiner et al. [15] developed a semianalytical method to estimate the well production in heterogeneous reservoirs. The permeability heterogeneity along the well was modeled by effective skin. Wang et al. [17] presented a new semianalytical method to investigate the production performance of a multifractured horizontal well in heterogeneous reservoirs. The effects of permeability heterogeneity, SRV heterogeneity, and drainage area heterogeneity on the Blasingame-type curves were discussed. The boundary element method, source functions, and Green's solution were used to develop a new method to study multifractured horizontal well production in heterogeneous gas reservoirs [18]. Results showed that a larger fracture half-length and higher fracture conductivity are beneficial to reduce the influence of crossflow.

Compared to the analytical and semianalytical methods, the numerical simulation methods are more convenient to study the transient flow and production problems in both homogeneous and heterogeneous reservoirs [19–29]. Yu et al. [19] discussed the effect of different fracture half-length combinations on the multifractured gas well production performance. The research showed that the multifractured horizontal gas well would get higher cumulative gas production with longer outer fractures. Olorode et al. [22] developed a new method to describe the complex fracture patterns. Based on their model, the production of an unconventional gas well was simulated. Their research showed that planar and orthogonal fractures would yield higher gas production. Liu et al. [24] pointed out that it is significant to take the threshold pressure gradient into consideration for the simulation of low-permeability gas and oil reservoirs. In their paper, pressure field diagrams and streamline field distribution diagrams at different times were used for analysis. He et al. [25] proposed a comprehensive optimization strategy for every single multifractured horizontal well in heterogeneous tight gas reservoirs. It is found that the measurement of non-Darcy flow character, the establishment of horizontal heterogeneous reservoir models, the induced stress model, and the design of operation parameters are the key steps to realize the optimization strategy. Guizada et al. [26] made full use of the pressure transient analysis to identify and interpret the reservoir properties. Subsequently, a large number of interpretation results were used as input variables in the simulation. Al-Fatlawi et al. [29] proposed a method to optimize multistage hydraulic fractured parameters by using a homogeneous model instead of a heterogeneous model in a heterogeneous tight gas reservoir.

In this paper, we established the corresponding geological models based on the heterogeneity characteristics of the tight gas reservoir, and the Eclipse software was used to simulate the production performance of several heterogeneous schemes. Based on the homogeneous scheme and four types of typical heterogeneous schemes, we discussed the effects of reservoir permeability level, length of horizontal well, and fracture half-length on the gas reservoir recovery in detail. Our research can provide some guidance for the layout of multifractured horizontal wells and fracturing design in heterogeneous tight gas reservoirs.

2. Heterogeneity Characteristics and Model Parameters

The Shaximiao gas reservoir of the Sichuan Basin, China, is a typical heterogeneous tight gas reservoir. At present, the success of multifractured horizontal wells has become the main benefits for gas reservoir development. The reservoir permeability ranges from 0.0008 mD to 1.75 mD with an average of 0.22 mD, while the porosity is mainly distributed in the interval of 7% to 13%. The reservoir shows a strong heterogeneity in both vertical and horizontal directions as illustrated in Figure 1.

Figure 1(a) presents a multifractured horizontal well in the gas reservoir with geological heterogeneity in the horizontal direction. In the direction along the horizontal well, the rectangular gas reservoir is divided into region A, region B, and region C. Reservoir region A is of length \( L_{rA} \) and permeability \( K_{rA} \), while the two other regions are of length \( L_{rB} \) and \( L_{rC} \), as well as permeability \( K_{rB} \) and \( K_{rC} \), respectively, with identical reservoir parameters. In the following numerical simulation study, parameter \( L_{rA} \) was set as 800 m, and both \( L_{rB} \) and \( L_{rC} \) were set as 400 m.

Figure 1(b) presents a multistage fractured horizontal well in the gas reservoir with geological heterogeneity in the vertical direction. In the direction perpendicular to the horizontal well, the rectangular gas reservoir is divided into region A, region B, and region C. Reservoir region A is of width \( W_{rA} \) and permeability \( K_{rA} \), while the two other regions share the same width and permeability, which are denoted as \( W_{rB} \) and \( W_{rC} \) as well as \( K_{rB} \) and \( K_{rC} \), respectively. In our study, \( W_{rA} \) was set as 300 m, and both \( W_{rB} \) and \( W_{rC} \) were set as 150 m.

As shown in Figures 1(a) and 1(b), the closed gas reservoir is of length \( L_{r} \), width \( W_{r} \), and thickness \( H_{r} \). The horizontal well is located in the central of reservoir region A with a length \( L_{w} \). The distances between one end of the horizontal well and the nearest reservoir boundary along the horizontal well are \( D_{wA} \) and \( D_{wA} \), which are equal in our study. The horizontal well is multistage fractured by 11 identical fractures with fracture half-length \( X_{f} \) and fracture conductivity \( C_{DF} \). Hydraulic fractures are considered to be infinitely conductive, so the dimensionless conductivity of fracture, \( C_{DF} \), was set as 300 in this paper. Note that the fracture width \( W_{f} \) is 0.5 m as the hydraulic fractures are treated by local grid refinement in simulation. The basic parameters of the gas reservoir model are shown in Table 1.
3. Basic Simulation Schemes

Based on the basic gas reservoir parameters, several numerical models for the development of a gas reservoir by a multi-stage fractured horizontal well were established. In our study, the Eclipse software was used for simulation. In order to analyze the effect of reservoir heterogeneity on gas well production, we also set up the corresponding homogeneous numerical simulation schemes for comparison.

Considering the heterogeneity distribution characteristics of the reservoir, we mainly discussed five types of numerical simulation schemes. Figure 2 presents the permeability distribution characteristics of the above-mentioned five schemes. CASE0 is a homogeneous scheme, and the matrix permeability was set as 0.22 mD in the whole reservoir. CASE1 and CASE2 are horizontally heterogeneous schemes (Figure 1(a)), while CASE3 and CASE4 are vertically heterogeneous schemes (Figure 1(b)). For the heterogeneous schemes, the permeability of low-permeability regions was set as 0.2 times that of high-permeability regions. The high-permeability region for CASE1 and CASE3 is assigned to region A, which, however, is the low-permeability region

### Table 1: Reservoir parameters of the basic simulation model.

| Parameter                  | Value | Parameter                  | Value |
|----------------------------|-------|----------------------------|-------|
| Reservoir length $L_r$ (m) | 1600  | Horizontal well length $L_w$ (m) | 800   |
| Reservoir width $W_r$ (m)  | 600   | Fracture numbers $N_f$      | 11    |
| Reservoir thickness $H_r$ (m) | 21   | Fracture spacing $F_s$ (m)  | 80    |
| Matrix porosity $\phi_m$ (%) | 10   | Fracture half-length $X_f$ (m) | 80   |
| Matrix permeability $K_m$ (mD) | 0–0.22 | Fracture width $W_f$ (m) | 0.5  |
| Well-boundary distance $D_{wb}$ (m) | 400 | Fracture conductivity $C_f$ | 300  |
| Gas saturation $S_{gi}$ (%) | 52    | Reservoir pressure $P_i$ (bar) | 459   |

**Figure 1:** Schematic of a multifractured horizontal well in the gas reservoir with geological heterogeneity.

**Figure 2:** Permeability distribution characteristics of five different schemes.
for CASE2 and CASE4. In the subsequent numerical simulation studies, the gas well production was simulated for 10 years, and the numerical simulation results were analyzed.

4. Results and Discussion

4.1. Characteristics of Streamline and Pressure Distribution.

Figures 3 and 4 show the streamline distribution and pressure distribution at different production stages for five cases, respectively. Figure 5 displays the cumulative gas reservoir recovery of different cases after 10 years of production.

CASE0. During the early and middle periods of production, the streamlines in the fracture control zone are relatively dense, indicating that the fractures have a great contribution to the gas production. With the development of gas well production, the streamlines around the horizontal well area are relatively sparse, and the production is mainly from the fractures at both ends of the horizontal well. Compared with the other four heterogeneous schemes, the homogeneous scheme CASE0 has a relatively high reservoir permeability, and the recovery degree of the gas reservoir is relatively uniform in space.

CASE1. Due to the relatively high permeability of region A (Figure 1(a)) and the hydraulic fractures located in the horizontal well area, the streamlines in the horizontal well area are more intensive in the early and middle stages, which is similar to CASE0. During the late period, the gas production is mainly supplied by region B/C (Figure 1(a)). However, due to the low permeability of region B/C, the production supply capacity is weak. Comparing the pressure distribution of CASE1 and CASE0 (Figure 4), we can see that, with the same production time, the recovery degree of central region A for CASE1 is higher, while it is lower in side region B/C.
CASE2. The streamline characteristics are obviously different from CASE0 and CASE1 (Figure 3). Horizontal well area region A (Figure 1(a)) has a relatively low reservoir permeability, where the gas is mainly produced by inner fractures. Hydraulic fractures and region A form a relatively stable seepage field. The gas in region B/C (Figure 1(a)) is mainly produced by two outer fractures. By comparing the pressure distribution diagrams of CASE2 and CASE1 (Figure 4), it can be found that the recovery degree for CASE2 is more uniform in space.

CASE3. Region A (Figure 1(b)) has a relatively high reservoir permeability, which results in a good gas supply capacity for the reservoir matrix at both ends of the horizontal well. As can be seen from the streamline distribution diagram, there is an obvious boundary between region A (high permeability) and region B/C (low permeability) (Figure 3). Comparing the pressure field distribution diagrams of CASE3 and CASE0 (Figure 4), we found that the pressure wave transmission of CASE3 presents a rectangular expansion, while it presents an ellipse expansion for CASE0.

CASE4. Contrary to CASE3, reservoir permeability of region A (Figure 1(b)) is lower than that of region B/C, resulting in a poor gas supply capacity for the reservoir matrix at both ends of the horizontal well. The streamline distribution characteristics are obviously different from CASE0 and CASE3, and the pressure consumption of gas flow increases, indicating that this is an unfavorable production mode. By comparing the pressure distribution characteristics of CASE4 and CASE3 (Figure 4), it can be observed that CASE3 is better in terms of the reserve exploitation at both ends of the horizontal well.

4.2. Analysis of Gas Production and Recovery. In order to further analyze the influence of reservoir heterogeneity on the production of gas well, it is necessary to compare the gas production data of different schemes (Figures 5–7). For CASE0, CASE1, CASE2, CASE3, and CASE4, the well can maintain a steady production rate for 4.46 years, 3.56 years, 3.48 years, 4.06 years, and 2.67 years, respectively, and the gas reservoir recovery after 10 years of production is 85.69%, 74.69%, 80.81%, 82.61%, and 72.63%, respectively. As shown in Figures 5 and 6, CASE0 presents the longest stable production time and the highest cumulative gas production among all the numerical modeling schemes.

Different reservoir heterogeneities show different effects on the reservoir development. By comparing the production curves of CASE1 and CASE2, it can be seen that the stable production periods of CASE1 and CASE2 are approximately equal, but the recovery of CASE2 is 6.12% higher than that of CASE1. The reservoir permeability of the unfractured areas determines the seepage ability of the reservoir matrix, which shows a great impact on the long-term production performance of the gas well. Comparing the production curves of CASE3 and CASE4, it can be found that the stable production period of CASE4 is shorter and the production decline
is faster. The recovery of CASE4 is 9.98% lower than that of CASE3. The reason is that the reservoir permeability at both ends of the horizontal well is poor and the gas supply capacity is weak in CASE4, which makes it difficult to effectively exploit the remaining reserves in region B/C (Figure 1(b)).

4.3. Effect of Reservoir Permeability Level on Reservoir Recovery. In heterogeneous tight gas reservoirs, the permeability distribution is very wide, so it is necessary to analyze the production performance of heterogeneous reservoirs under different reservoir permeability levels. Therefore, the permeabilities in the high-permeability region for each heterogeneous case are set as 0.22 mD, 0.11 mD, 0.044 mD, and 0.022 mD, respectively, and the corresponding permeabilities in the low-permeability region are 0.044 mD, 0.022 mD, 0.0088 mD, and 0.0044 mD, respectively. The numerical simulation results of different schemes are shown in Figure 8. As shown in Figure 8, the gas reservoir recoveries under different schemes all show an increasing tendency with the increase in permeability level, and the curve characteristics of other schemes are similar to that of CASE0.

By comparing CASE1 and CASE2, when the permeability level is relatively low, the recovery of CASE1 is higher. For example, when the permeability is 0.022 mD, the recovery of CASE1 is 46.01%, while the recovery of CASE2 is 41.66%. At high permeability level, the production performance of CASE2 is better than that of CASE1. When the matrix permeabilities are 0.044 mD, 0.11 mD, and 0.22 mD, the recoveries of CASE2 are 0.11%, 5.49%, and 6.12% higher than those of CASE1, respectively. By comparing CASE3 and CASE4, the production performance of CASE3 is better under the same permeability conditions, and the recoveries of CASE3 exceed those of CASE4 by 9.98%-17.09%.

4.4. Effect of Horizontal Well Length on Reservoir Recovery. Figure 9 shows the effect of well length on the cumulative gas reservoir recovery of the five cases. In the numerical simulation schemes, we assumed that the multifractured horizontal well is located in the central of the gas reservoir. We set the length of the horizontal well to be 480 m, 640 m, 800 m, and 960 m, respectively. As shown in Figure 9, the reservoir recovery of different simulation cases increases with the increase in horizontal well length.

It should be noted that when the length of the horizontal well is 800 m, the outer 2 fractures in CASE1 and CASE2 are just located at the interface of region A and region B/C (Figure 1(a)). When the length of the horizontal well is longer than 800 m, the hydraulic fractures of the horizontal well can effectively control the heterogeneous region B/C (Figure 1(a)), and the recovery of CASE2 is higher than that of CASE1. If the length of the horizontal well is less than 800 m, there are no fracture communication channels between region B/C and the horizontal well, and the gas flow mainly depends on the seepage capacity of the reservoir matrix, which is unfavorable for the production in CASE2. We can see that when the lengths of the horizontal well are 480 m and 640 m, the recoveries of CASE1 exceed those of CASE2 by 14.59% and 7.29%, respectively. Compared with CASE4, CASE3 exhibits better production performance under all the horizontal well length conditions in this work. We can observe that with the increase in horizontal well length, the difference of recovery between CASE3 and CASE4 gradually decreases. When the lengths of the horizontal well are 480 m and 960 m, the recovery differences between CASE3 and CASE4 are 13.51% and 7.69%, respectively.

4.5. Effect of Fracture Half-Length on Reservoir Recovery. Figure 10 displays the effect of fracture half-length on the cumulative gas reservoir recovery of the five cases. We set the fracture half-length to be 80 m, 120 m, 160 m, and 200 m, respectively. As shown in Figure 10, as the fracture
Based on our research, several key conclusions can be drawn.

1. Based on the heterogeneity characteristics of the tight gas reservoir, the homogeneous scheme and four typical heterogeneous schemes were established to simulate the production of a multifractured horizontal well. The production characteristics and differences between different schemes were analyzed by streamline distribution, pressure distribution, and production data. Based on the homogeneous and heterogeneous schemes, the effects of reservoir permeability level, length of horizontal well, and fracture half-length on the gas reservoir recovery were discussed in detail.

2. The reservoir permeability of the unfractured areas determines the seepage ability of the reservoir matrix, which shows a great impact on the long-term production performance of the gas well. In the development of heterogeneous tight gas reservoirs with a multifractured horizontal well, the key to improve the development efficiency is to fully and effectively exploit the gas reserves in the unfractured areas.

3. Compared with the homogeneous scheme, different heterogeneous schemes show negative effects on the gas production. High reservoir permeability level, long horizontal well length, and long fracture half-length are beneficial to reduce the adverse influence of heterogeneity on the gas production.

4. For the horizontal heterogeneity, the reservoir matrix permeability level and the horizontal well length impose a great influence on the recovery difference of the two types of heterogeneous schemes. For the vertical heterogeneity, the fracture half-length has a significant impact on the recovery difference of the two different heterogeneous schemes.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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