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Research Article

Productivity Formula of Horizontal Well in Low-Permeability Gas Reservoir considering Multiple Factors

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For horizontal well in low-permeability gas reservoir, the effects of threshold pressure gradient, stress sensitivity, and gas slippage have significant impacts on the well productivity. At present, there are few productivity formulas for horizontal gas well considering all these factors. In this paper, based on the flow analysis of horizontal well in low-permeability gas reservoir, the whole flow field was divided into two parts, namely, far wellbore region and near wellbore region, among which the far wellbore region is composed of plane linear flow region and plane radial flow region and the near wellbore region is composed of vertical plane radial flow region and spherical plane central flow region. Then, a new productivity formula is established based on the steady-state seepage theory and the equivalent seepage resistance method, with the consideration of threshold pressure gradient, stress sensitivity, and gas slippage effect. The accuracy of the formula in this paper is verified through comparing with other classical models, and the influence of various factors on the well productivity is analyzed. The analysis results show that stress sensitivity has the most significant effect on horizontal gas well production, followed by threshold pressure gradient, and the gas slippage has the least effect. With the consideration of all influencing factors, the higher the formation pressure and reservoir thickness, the higher the productivity, and the increase of productivity increases with the increase of flow pressure difference. The increasing trend of gas productivity index per meter with the increase of reservoir permeability is first fast and then slow. When the reservoir permeability is greater than 1.2 mD, the increment of gas productivity index per meter (MGPI) decreases. When the length of horizontal well is greater than 1400 m, the increment of gas productivity index per meter decreases with the increase of gas reservoir thickness. Therefore, it is recommended to control the horizontal well length within 1400 m in low-permeability gas reservoir. In addition, the absolute open flow charts corresponding to reservoir thickness and horizontal well length under different reservoir permeability conditions were also given, which can provide theoretical guidance for the selection of horizontal well length during the development of low-permeability gas reservoirs.

1. Introduction

With the development of conventional resources, more and more attention is paid to unconventional oil and gas resources (low permeability/shale, etc.) [1, 2]. At present, horizontal wells have become the main way to develop low-permeability gas reservoirs with large reserves, difficult exploitation, and low productivity [3]. Owing to the high irreducible water saturation of low-permeability gas reservoir, the gas water flow channel is narrowed, which not only has the stress sensitivity effect but also has the threshold pressure gradient. Compared with low-permeability reservoirs, gas slippage effect has to be considered in gas reservoir, which makes it more difficult to study the gas reservoir percolation model, and it is difficult to analyze its flow law with the conventional Darcy percolation law [4].

Domestic and foreign scholars have carried out a wealth of research on the productivity of horizontal wells. Borisov [5] established a simple model to calculate the productivity of horizontal well with an equivalent flow resistivity concept. Giger et al. [6] published a similar equation for the inflow of horizontal well. Later, Joshi [7] combined two 2D flows and presented an analytical equation for the productivity of horizontal well. Renard and Dupuy [8] also established a model for horizontal wells. All the above models are for steady-state flow. Kuchuk et al. [9] and Babu and Odeh [10] published a model to calculate the productivity of horizontal wells under pseudo-steady-state conditions. Goode and Kuchuk [11] developed a further improved model. Kuppe and Settari [12] applied numerical model to study the productivity index of horizontal wells. Helmy and Wattenbarger [13] developed a simplified equation to compute the productivities for horizontal wells producing constant rate and pressure. Based on the Joshi and Giger formulas, Yuanqian [14] converted the seepage into two two-dimensional planar seepage, namely, horizontal seepage and vertical seepage, and then established the productivity formula of Yuanqian's horizontal well by using the equivalent seepage resistance method. Based on the Joshi formula, Xiao and Yong [15], Haihong et al. [16], Qiguo et al. [17], and Xue et al. [18] established different productivity formulas for horizontal wells by introducing different considerations. Maolin et al. [19], based on the similarity principle of gas phase and liquid phase seepage, found that the productivity equation of gas well and oil well is similar in form, and the productivity equation of horizontal gas wells can be obtained by using the productivity equation of horizontal oil wells. Mingqiang et al. [20], Chen et al. [21], Yanfang et al. [22], and Gao et al. [23] divided the seepage field near the horizontal wells of low-permeability oil and gas reservoirs into far well area and near well area for separate analysis and obtained new analytical formulas for production calculation. Fuquan [24] deduced a horizontal well productivity model with pressure sensitive effect by considering the medium deformation of low-permeability oil and gas reservoirs. Liehui et al. [25] introduced conformal transformation to derive the productivity model of horizontal wells in low-permeability gas reservoirs by simultaneously considering the impact of starting pressure gradient and high-speed non-Darcy effect. Lu et al. [26] established a new productivity evaluation model for multicluster fractured wells based on volumetric source method. Hailong et al. [27] adopted the effective stress function of the body rock, considered the change of medium porosity, and applied variable substitution and variable separation methods to derive the productivity model of horizontal wells in low-permeability gas permeable reservoirs which considered both the stress sensitivity effect and the influence of starting pressure gradient.

The above researches mainly focus on the flow field splitting method and parameter correction, while few researches involve the productivity formula of horizontal wells that comprehensively considers the threshold pressure gradient, stress sensitivity, gas slippage effect, and other factors in low-permeability gas reservoirs.

Therefore, on the basis of analyzing the seepage characteristics of horizontal well development in low-permeability gas reservoir, this paper uses the flow field splitting method to split the seepage field of horizontal wells into the far well area and the near well area, and then, through the stable seepage theory and the equivalent seepage resistance method, a formula for calculating the productivity of horizontal gas well in low-permeability gas reservoir is given, which comprehensively considers such factors as starting pressure gradient, stress sensitivity, and slippage effect and conducts accuracy verification and impact factor analysis. It is expected to provide theoretical support for the optimal design of horizontal well development in low-permeability gas reservoirs.

2. Recognition and Simplification of Horizontal Well Seepage Field

Assuming that the circular gas reservoir is homogeneous and isotropic, a horizontal well is available in its center, which is parallel to the top and bottom of the gas reservoir; besides, the basic parameters are length of the horizontal well section L, wellbore radius r_w, gas reservoir thickness h, and supply radius r_e. The shape of gas discharged from horizontal wells is generally expressed as an ellipsoid. However, horizontal wells are mostly used in thin gas reservoirs, the gas discharged from which only occupies a part of the ellipsoid as often as possible, as shown in Figure 1. Therefore, the seepage field of this kind of thin gas reservoir can be simplified into the seepage field as shown in Figure 2 in the horizontal plane (xy plane).

According to the geometric shape of venting gas shown in Figure 2, the venting area of xy plane can be expressed as

$$A = bL + \frac{\pi}{4} b^2, \tag{1}$$

where b is the deflating width on xy plane (m), L is the length of horizontal section of horizontal well (m), and A is the deflating area on the xy plane (m^2).

On account of the small thickness, the drainage area can be equivalent to the drainage area as shown in Figure 3. In this paper, small thickness means the ratio of reservoir thickness to horizontal length in less than 0.08, which is typical for low-permeability gas reservoir in Sichuan basin, China. The drainage area can be approximately decomposed into the part of far wellbore (including two rectangles and two half cylinders) and the part of near wellbore (including the parts of orange cylinder and two orange hemispheres). The flow fluid in the formation, based on the fluid process from the formation to the wellbore, can be divided into two stages: (1) the flow stage on far wellbore, that is, the fluid flows from the gas supply edge of the gas reservoir to the external surface of the near wellbore gas release with the wellbore as the center and $h/2$ as the radius, and (2) flow stage near wellbore, namely, the fluid flows from the near wellbore external surface to the horizontal wellbore.

As per the above simplified model of equivalent watershed area of horizontal wells, there exist two correlation conditions in the far wellbore flow area as well as near wellbore flow area of horizontal wells:

(1) The pressure on the interface between the far wellbore flow area and the near wellbore flow area is consistent, that is, $P_{\mathrm{ff}} = P_{\mathrm{fn}} = P_f$

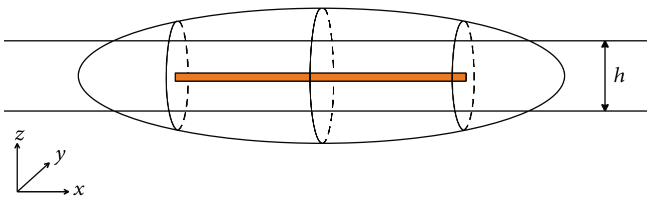


FIGURE 1: Equivalent seepage of horizontal well in thin reservoir.

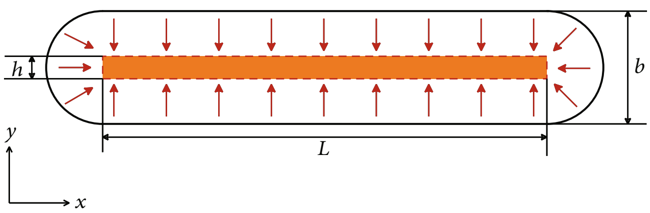


FIGURE 2: Simplified seepage of horizontal well in thin reservoir in *xy* plane.

(2) The total flow in the far wellbore flow area is equal to the total flow in the near wellbore flow area, that is, $Q_{scf} = Q_{scn} = Q_{sc}$

3. New Productivity Formula of Horizontal Well in Low-Permeability Gas Reservoir

3.1. Correction of Gas Motion Equation. Problems such as slippage effect, low speed nonlinear seepage, and stress sensitivity often occur in low-permeability tight sandstone gas reservoirs [28, 29] on account of the particularity of the reservoir. In low-permeability gas reservoirs, moving in the small pores of the reservoir, the gas, more often than not, collides with the wall of the pores, resulting in a thin layer of adsorption, that is, slippage effect. The gas flow equation, considering slippage effect, can be expressed as [30]

$$v = -\frac{K\left(1 + b/\bar{P}\right)}{\mu}\frac{dP}{dr}, \tag{2}$$

where v is the gas velocity (m/s), K is reservoir permeability (μm^2), μ is the gas viscosity (Pa·s), b is the slippage factor (Pa), $\bar{P}$ is the average pressure (Pa), and P is the formation pressure (Pa).

As the gas moves from static state to moving state at the same time, it also needs to overcome the resistance caused by the hydration film at the small pore throat, which means that there is a threshold pressure gradient. The gas flow after considering the threshold pressure gradient can be expressed as [31]

$$v = -\frac{K}{\mu}\left(\frac{dP}{dr} - \lambda\right), \tag{3}$$

where λ is the threshold pressure gradient (Pa/m).

In addition, owing to their complex pore structure and small throat, as the stress on the reservoir rocks changes during the development process, they show a strong stress sensitivity effect as often as possible in low-permeability reservoir rocks. Stress sensitivity is usually expressed by the following empirical formula [32]:

$$K = K_i e^{\alpha(P-P_i)}, \tag{4}$$

where K is the reservoir permeability under any formation pressure (μm^2), K_i is the reservoir permeability under the original formation pressure (μm^2), α is the stress sensitivity coefficient (Pa^{-1}), P is the formation pressure (Pa), and P_i is the original formation pressure (Pa).

In the development of low-permeability tight gas reservoirs, it has been confirmed that stress sensitivity has an important impact on productivity. Although there is no unified understanding of whether the low speed non-Darcy phenomenon has an impact, it is still of great significance to study its impact laws and trends to guide the formulation of technical policies for the development of low-permeability tight gas reservoirs.

Combined with equations (2), (3), and (4), the modified gas motion equation can be expressed as

$$v = -\frac{K_i\left(1 + b/\bar{P}\right)e^{\alpha(P-P_i)}}{\mu}\left(\frac{dP}{dr} - \lambda\right). \tag{5}$$

3.2. Equivalent Seepage Method. In the actual reservoir, a common method to simplify the problem without affecting the accuracy is to use the circuit flow law to describe the liquid seepage process according to the similarity of liquid flow and current and then solve it according to Kirchhoff's law. This method of solving the seepage problem by using the principle of hydropower similarity is called the equivalent seepage resistance method [33].

$$Q = \frac{\Delta P}{R}, \tag{6}$$

where Q is the flow (m^3/s), ΔP is the seepage pressure difference (Pa), and R is seepage resistance (MPa·s/m^3).

3.3. Calculation for Resistance in Far Wellbore Flow Area. The flow in the far wellbore area can be further divided into two parts: the plane linear flow in the rectangular part (① in Figure 3) and the plane radial flow in the semicylindrical part (② in Figure 3).

For planar linear flow, the fluid flows from the outer edge of gas supply in the gas reservoir to the outer surface of the near well flow area (cylinder) with the axis of the wellbore and $h/2$ as the radius. Its productivity formula can be expressed as

$$\frac{Q_{sc1}}{2Lh}\frac{P_{sc}T}{T_{sc}} = \frac{K_i\left(1 + b/\bar{P}\right)e^{\alpha(P-P_i)}}{\mu Z}\left(\frac{dP}{dx} - \lambda\right), \tag{7}$$

where Q_{sc1} is the plane linear flow rate in the far wellbore

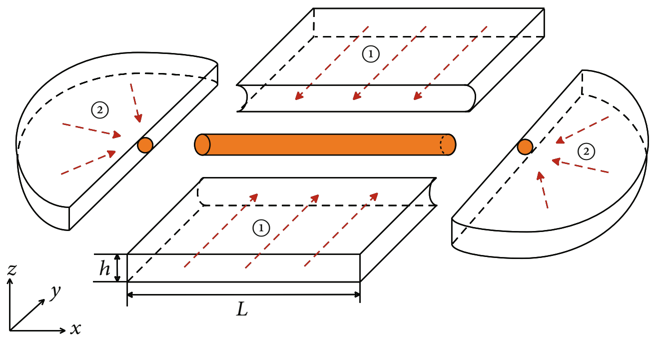


FIGURE 3: Three-dimensional illustration of simplified seepage.

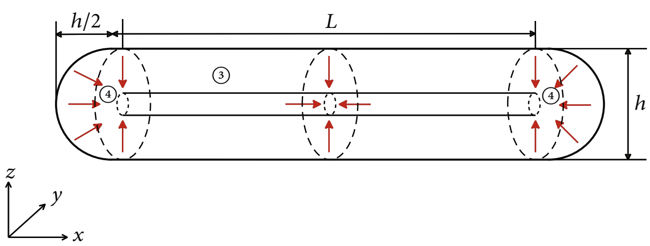


FIGURE 4: Illustration of seepage near the horizontal well.

area (m^3/s); P_{sc} is the atmospheric pressure under the ground standard state, taking 101325 Pa; T_{sc} is the ground standard temperature, 293.15 K; T is the gas temperature (K); and Z is the compression factor.

According to the equivalent seepage resistance method, the seepage resistance of the plane linear flow process in the flow stage in the far wellbore area can be expressed as

$$R_{11} = \frac{P_{sc}T((b/2)-(h/2))}{2LhT_{sc}K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}}. \tag{8}$$

For planar radial flow, two semicylindrical deflators can be combined and treated as the fluid with $b/2$ as the outer boundary and flowing to the outer surface of the near well deflator with $h/2$ as the radius. The productivity formula can be expressed as

$$\frac{Q_{sc2}}{2\pi rh}\frac{P_{sc}T}{T_{sc}} = \frac{K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}}{\mu Z}\left(\frac{dP}{dr}-\lambda\right), \tag{9}$$

where Q_{sc2} is the plane radial flow rate in the far wellbore area (m^3/s).

The seepage resistance of the plane radial flow process in the flow stage in the far wellbore area can be expressed as

$$R_{12} = \frac{P_{sc}T\ln b/h}{2\pi hT_{sc}K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}}. \tag{10}$$

Then, the total flow in the flow stage in the far wellbore area is $Q_{scf} = Q_{sc1} + Q_{sc2}$, and the equivalent seepage resistance can be expressed $R_1 = \Delta P_1/Q_{scf}$, so the total seepage resistance in the flow stage on the far wellbore area is recorded as

$$R_1 = \frac{R_{11}R_{12}}{R_{11}+R_{12}} = \frac{P_{sc}T(b-h)\ln b/h}{2\pi hT_{sc}K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}(b-h+(2L/\pi)\ln b/h)}. \tag{11}$$

3.4. Calculation of Seepage Resistance in Near Wellbore Flow Area. Having been completed the flow stage in the far wellbore area, it will enter the flow stage in the near wellbore area, the seepage field of which is shown in Figure 4. It can also be divided into two parts: the vertical plane radial flow of the cylinder part (number ③ in Figure 4) and the spherical centripetal flow of the spherical part (number ④ in Figure 4).

The fluid, for the vertical plane radial flow, flows from the outer surface of the gas near the well with the radius of $h/2$ to the wellbore with the radius of r_w through the plane radial flow, and its productivity formula can be expressed as

$$\frac{Q_{sc3}}{2\pi rL}\frac{P_{sc}T}{T_{sc}} = \frac{K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}}{\mu Z}\left(\frac{dP}{dr}-\lambda\right), \tag{12}$$

where Q_{sc3} is the vertical plane radial flow rate in the flow stage near wellbore (m^3/s).

The seepage resistance of the vertical plane radial flow process in the near wellbore area flow stage can be expressed as

$$R_{21} = \frac{P_{sc}T\ln h/2r_w}{2\pi LT_{sc}K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}}. \tag{13}$$

The two hemispherical gas discharges can be combined and treated for spherical centripetal flow, as fluid, through the spherical centripetal, flows into the wellbore with radius r_w from the near wellbore external surface with radius $h/2$, and its productivity formula can be expressed as

$$\frac{Q_{sc4}}{4\pi r^2}\frac{P_{sc}T}{T_{sc}} = \frac{K_i\left(1+b/\bar{P}\right)e^{\alpha(P-P_i)}}{\mu Z}\left(\frac{dP}{dr}-\lambda\right), \tag{14}$$

where Q_{sc4} is the flow rate of ball to heart in the near wellbore flow stage (m^3/s).

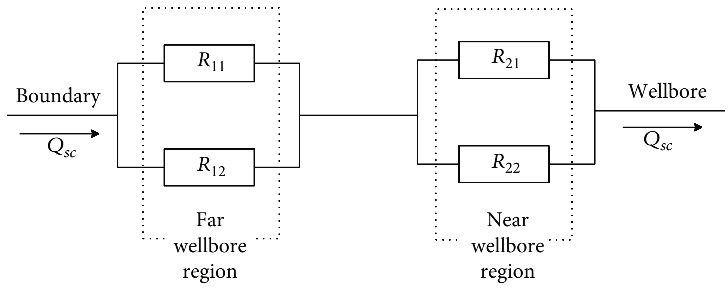


Figure 5: Circuit diagram of the simplified model.

The seepage resistance in the process of ball to center flow in the near wellbore area flow stage can be expressed as

$$R_{22} = \frac{P_{sc} T((1/r_w) - (2/h))}{4\pi T_{sc} K_i \left(1 + b/\bar{P}\right) e^{\alpha(P-P_i)}}. \quad (15)$$

Similarly, the total seepage resistance in the flow stage near wellbore can be expressed as

$$R_2 = \frac{R_{21} R_{22}}{R_{21} + R_{22}} = \frac{P_{sc} T \ln h/2r_w((1/r_w) - (2/h))}{4\pi T_{sc} K_i \left(1 + b/\bar{P}\right) e^{\alpha(P-P_i)} (\ln h/2r_w + (L/2r_w) - (L/h))}. \quad (16)$$

3.5. New Productivity Formula for Horizontal Wells. According to the similar principle of gas phase seepage and liquid phase seepage, the equivalent seepage resistance method can be applied to gas reservoirs. The circuit diagram shown in Figure 5 is obtained from the simplified gas leakage and equivalent decomposition owing to the equivalent seepage theory.

From $Q_{sc} = Q_{sc1} + Q_{sc2} = Q_{sc3} + Q_{sc4}$, $\Delta P_1 + \Delta P_2 = \Delta P$, and $R = \Delta P / Q_{sc}$, it can be obtained that the total seepage resistance from the outer boundary of gas supply to the wellbore is

$$R = R_1 + R_2 = \frac{P_{sc} T}{2\pi h T_{sc} K_i \left(1 + b/\bar{P}\right) e^{\alpha(P-P_i)}} \cdot \left[\frac{(b-h) \ln b/h}{(b - h + (2L/\pi) \ln b/h)} + \frac{\ln h/2r_w((1/r_w) - (2/h))}{2/h \ln h/2r_w + (L/h)((1/r_w) - (2/h))} \right]. \quad (17)$$

Order $f(P) = P e^{\alpha(P-P_i)} / \mu Z$, define the pseudopressure

$$m(P) = \int_0^P f(P) dP, \quad (18)$$

where $m(P_e)$ is the pseudopressure at the supply boundary ($Pa^2/Pa{\cdot}s$) and $m(P_f)$ is the pseudopressure of the contact surface between the far wellbore area and the near wellbore area ($Pa^2/Pa{\cdot}s$).

Substituting equations (17) and (18) into equation (5), we can get the productivity calculation equation of horizontal gas well under the joint action of three factors: stress sensitivity, threshold pressure gradient, and slippage effect:

$$Q_{sc} = \frac{2\pi h T_{sc} K_i e^{-\alpha P_i} \left(1 + b/\bar{P}\right) \left(m(P_e) - m(P_w) - \lambda \int_{h/2}^{b/2} f(P) dx - \lambda \int_{r_w}^{h/2} f(P) dx \right)}{P_{sc} T [(((b-h) \ln b/h)/(b - h + (2L/\pi) \ln b/h)) + ((\ln h/2r_w((1/r_w) - (2/h)))/(2/h \ln h/2r_w + (L/h)((1/r_w) - (2/h))))]}. \quad (19)$$

It is easy to know that the formula is analytical and can be solved directly. Set $\lambda = 0$, $\alpha = 0$, and $b = 0$; the productivity equation can be obtained without considering the threshold pressure gradient, stress sensitivity, and slippage effect:

$$Q_{sc} = \frac{2\pi h T_{sc} K_i (m(P_e) - m(P_w))}{P_{sc} T [(((b-h) \ln b/h)/(b - h + (2L/\pi) \ln b/h)) + ((\ln h/2r_w((1/r_w) - (2/h)))/(2/h \ln h/2r_w + (L/h)((1/r_w) - (2/h))))]}. \quad (20)$$

Table 1: Calculation parameter.

Well name	Formation pressure (MPa)	Thickness (m)	Wellbore radius (m)	Horizontal length (m)	Well spacing radius (m)	Reservoir temperature (K)	Threshold pressure gradient (MPa/m)	Stress sensitivity index (MPa^{-1})	Slip-off factor	Permeability (mD)	Actual AOF (10^4 m^3/d)
QL203h1	17.43	13	0.107	531.5	770	341.5			0	0.16	47
QL205h1	17.08	17.80	0.107	362	640	344.0	0.04	0.02	0.3	0.09	9.3
QL205h2	20.77	17.80	0.107	843	810	342.8			0	0.57	39

Table 2: The comparison results of the horizontal well productivity prediction.

Model	QL203h1		QL205h1		QL205h2	
	Yield (10^4 m^3/d)	Deviation rate (%)	Yield (10^4 m^3/d)	Deviation rate (%)	Yield (10^4 m^3/d)	Deviation rate (%)
Borisov formula	54.48	15.90	11.99	28.97	46.36	18.86
Giger formula	51.44	9.45	11.93	28.31	45.33	16.23
Joshi formula	53.63	14.11	11.71	25.94	45.75	17.30
Yuanqian formula	53.78	14.42	11.71	25.95	45.77	17.35
Formula in this paper	50.92	8.35	10.26	10.35	40.47	3.78
Actual AOF	47	0	9.3	0	39	0

4. Verification of New Productivity Formula for Horizontal Wells and Analysis of Influencing Factors

Taking the well of low-permeability gas reservoir in central Sichuan as an example, the actual productivity is calculated to verify the rationality of the formula. Wells QL203h1, QL205h1, and QL205h2 are the three developed horizontal wells in the field. Formation parameters, fluid parameters, and well parameters are shown in Table 1.

4.1. Verification of New Formula. Based on the principle of formal similarity between gas seepage and liquid seepage in the seepage equation, the productivity formula for horizontal wells in some reservoirs can be transformed, the pseudopressure term and pressure term can be similarly replaced, and the above parameters are used for comparison [16]. In this paper, four classical formulas, Borisov's formula [3], Giger's formula [4], Joshi's formula [5], and Yuanqian's formula [12], are similarly replaced, with the comparison between the calculation results of these four improved formulas plus the new formula in this paper and the AOF obtained from well testing. The basic data in Table 1 was used. The productivity of the four classical formulas and the productivity of the new formula of the three horizontal wells were calculated, and the comparison results are shown in Table 2. It can be seen that the calculated results of the new formula in this paper are most similar to the actual production results, which can be used to predict the productivity of horizontal wells in low-permeability gas reservoirs.

4.2. Analysis of Influencing Factors

4.2.1. Effect of Stress Sensitivity, Threshold Pressure Gradient, and Slippage Effect on Productivity. Select QL203h1-related parameters as basic parameters, and the IPR curves of the above gas wells are obtained by using the model considering different influencing factors to compare the effects of various factors on the production performance of gas wells. The results are shown in Figure 6.

It can be found that the shape of IPR curve of each model is basically similar, and the rate of production increase slows down with the decrease of bottom-hole flowing pressure. Compared with the calculation results without considering any influencing factors, the stress sensitivity has the greatest impact on the single well productivity. After considering the stress sensitivity, the single well productivity will be significantly reduced; in addition, with the reduction of bottom-hole flow pressure, the impact of stress sensitivity on the single well productivity will become more obvious; the threshold pressure has the second effect on the single well productivity. The IPR curve will move to the left as a whole, and the single well productivity will decrease after considering the threshold pressure gradient; the slippage effect has the least impact on the productivity of the single well, and the slippage effect tends to increase productivity. When the production differential pressure is less than about 10 MPa, the slippage effect is not obvious while when the production differential pressure is greater than 10 MPa, the impact on productivity will appear gradually as the bottom-hole flow pressure decreases. After comprehensive consideration of stress sensitivity, threshold pressure gradient, and slippage effect, the productivity of the single well will be reduced greatly, and the AOF will decrease from 59.45×10^4 m^3/d to 50.92×10^4 m^3/d, with a decline rate of 14%, which shows that it is necessary to consider the above factors in the single well productivity calculation formula; otherwise, the single well productivity level will be significantly overestimated.

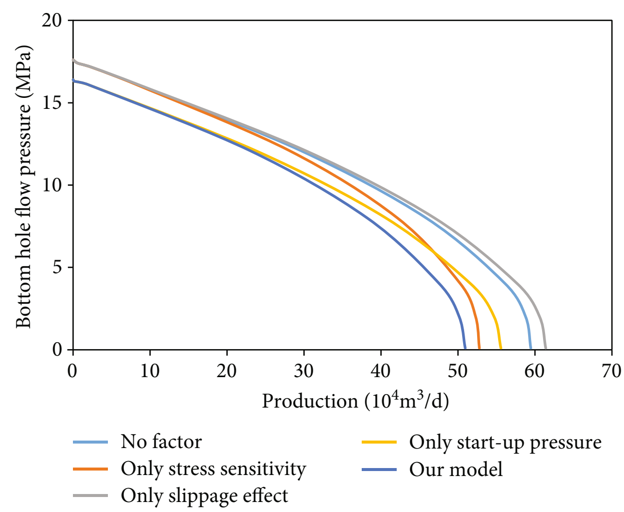


Figure 6: The IPR curve of different production models.

Through the above analysis, it can be found that for gas wells, stress sensitive effect, threshold pressure gradient, and slippage effect have a significant impact on the productivity of a single well. In order to further quantify and analyze

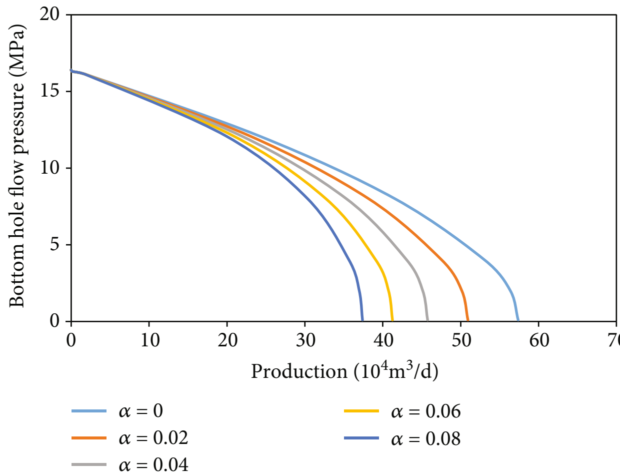


Figure 7: Influence of stress sensitivity on productivity.

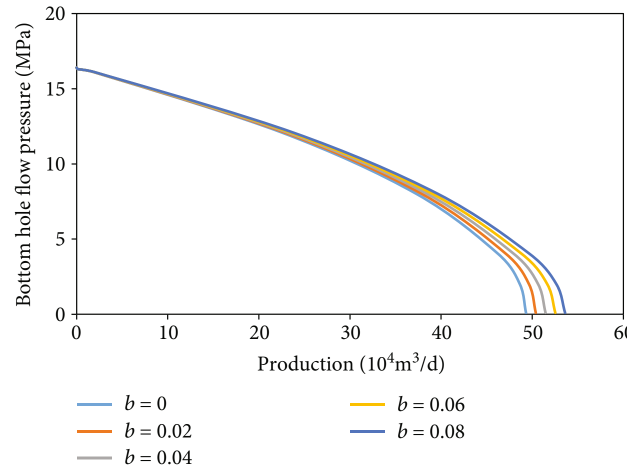


Figure 9: Influence of slippage effect on productivity.

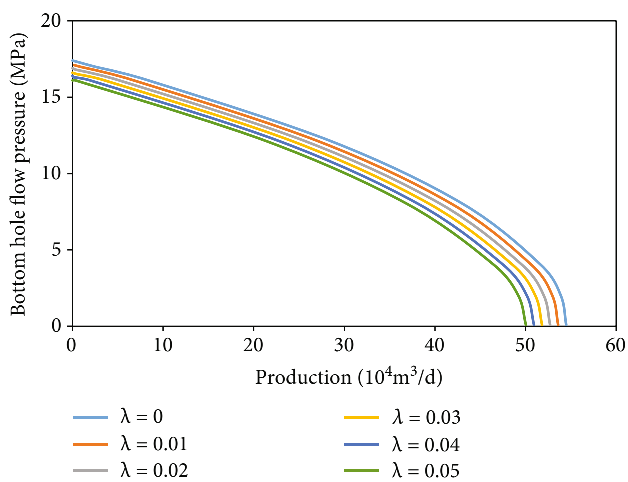


Figure 8: Influence of threshold pressure gradient on productivity.

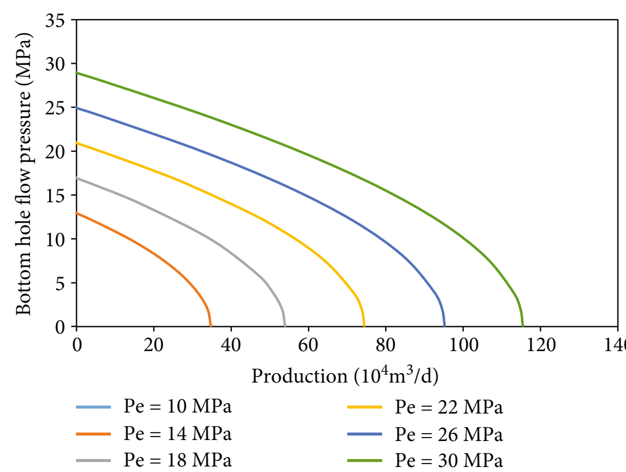


Figure 10: Influence of formation pressure on productivity.

the specific influence rules of various factors on the production performance of gas wells, the control variable method is used to analyze the influence factors, respectively, so as to obtain the changes of gas well IPR curve with various factors.

(1) Stress Sensitive Effect. The stress sensitivity coefficient was set as 0, 0.02, 0.04, 0.06, and 0.08 successively, and the IPR curve of a single well was calculated, as shown in Figure 7. It can be seen from the figure that the effect of stress sensitivity on single well productivity is very significant, which will lead to a significant decline in single well productivity, and this phenomenon is more obvious when the bottom-hole flow pressure is low. With the increase of stress sensitivity coefficient, the stress sensitivity effect is gradually enhanced; besides, the decline of the single well productivity is gradually increased as well. Compared with the stress sensitivity effect in lack of consideration, as the stress sensitivity coefficient is 0.04, the AOF of a single well is 46.12×10^4 m^3/d, decreased by 20.48%; as the stress sensitivity coefficient is 0.08, the AOF of the single well is 37.85×10^4 m^3/d, decreased by 34.74%.

(2) Threshold Pressure Gradient. Set the threshold pressure gradient to 0, 0.01, 0.02, 0.03, 0.04, and 0.05 successively, and the IPR curve of a single well was calculated, as shown in Figure 8. It can be seen from the figure that the existence of threshold pressure gradient will lead to the reduction of gas well productivity. With the increase of threshold pressure gradient, the reduction of the single well productivity will show a uniform trend, and the IPR curve will gradually move to the left. The greater the threshold pressure gradient, the more obvious the decline of gas well productivity. Compared with the threshold pressure gradient in lack of consideration, as the threshold pressure gradient is 0.03, the AOF of a single well is 53.11×10^4 m^3/d, decreased by 5.16%; as the threshold pressure gradient is 0.05, the AOF of the single well is 50.09×10^4 m^3/d, decreased by 10.55%.

(3) Slippage Effect. Set the slippage factors as 0, 0.2, 0.4, 0.6, and 0.8 one after another, and calculate the IPR curve of the single well as shown in Figure 9. It can be seen from the figure that under the conditions of high bottom-hole

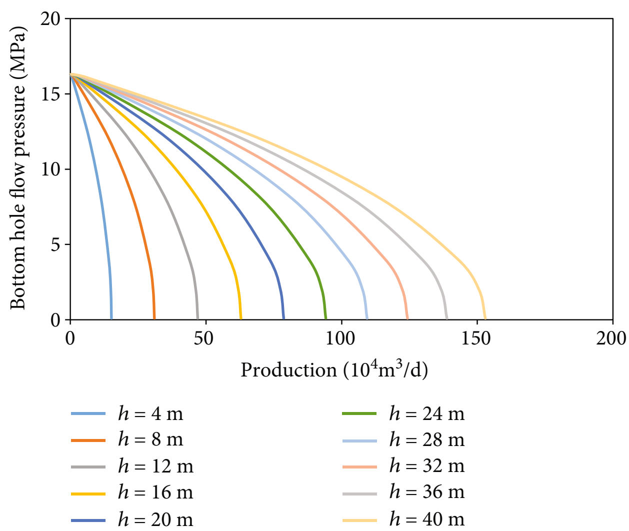


FIGURE 11: Influence of reservoir thickness on productivity.

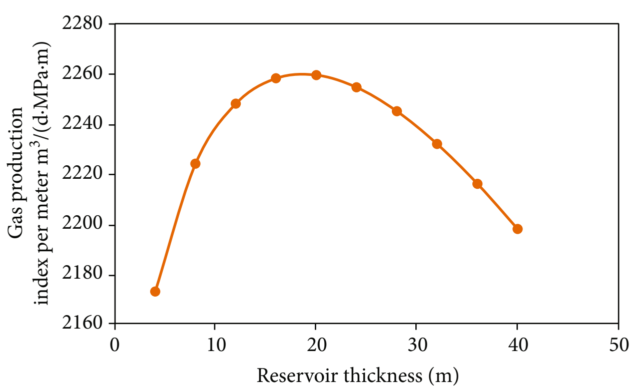


FIGURE 12: Influence of reservoir thickness on gas production index per meter.

flow pressure as well as low production differential pressure, the slippage effect has no obvious impact on the productivity of the single well; under the condition of low bottom-hole flowing pressure and high production differential pressure, the existence of slippage effect will increase the single well productivity to a certain extent. As far as this example is concerned, the critical bottom-hole flowing pressure of the slippage effect affecting the productivity of a single well is about 10 MPa, with the corresponding critical production differential pressure being 7.43 MPa. Compared with the slippage effect in lack of consideration, as the slippage factor is 0.4, the AOF of a single well is $52.11 \times 10^4\ m^3/d$, with an increase of 5.92%; as the slip factor is 0.8, the open flow capacity rate of the single well is $54.23 \times 10^4\ m^3/d$, with an increase of 10.22%.

4.2.2. Influence of Geological Conditions on Productivity. In order to analyze the influence of reservoir geological conditions on gas well productivity, the influence of changes in formation parameters such as formation pressure, reservoir thickness, and reservoir permeability on single well production performance under the premise of considering stress sensitivity, threshold pressure gradient, and slippage effect is further analyzed.

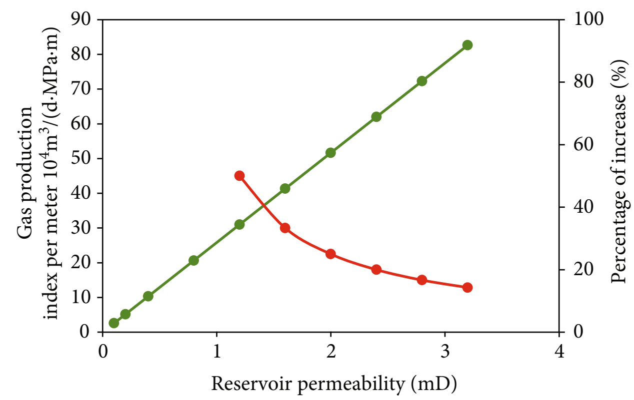


FIGURE 13: Influence of reservoir permeability on gas production index per meter.

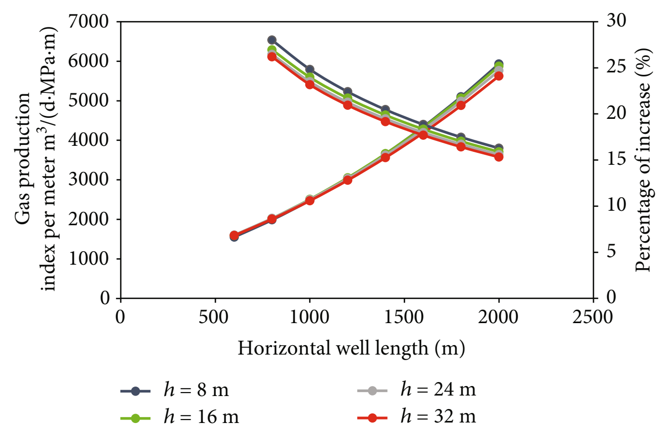
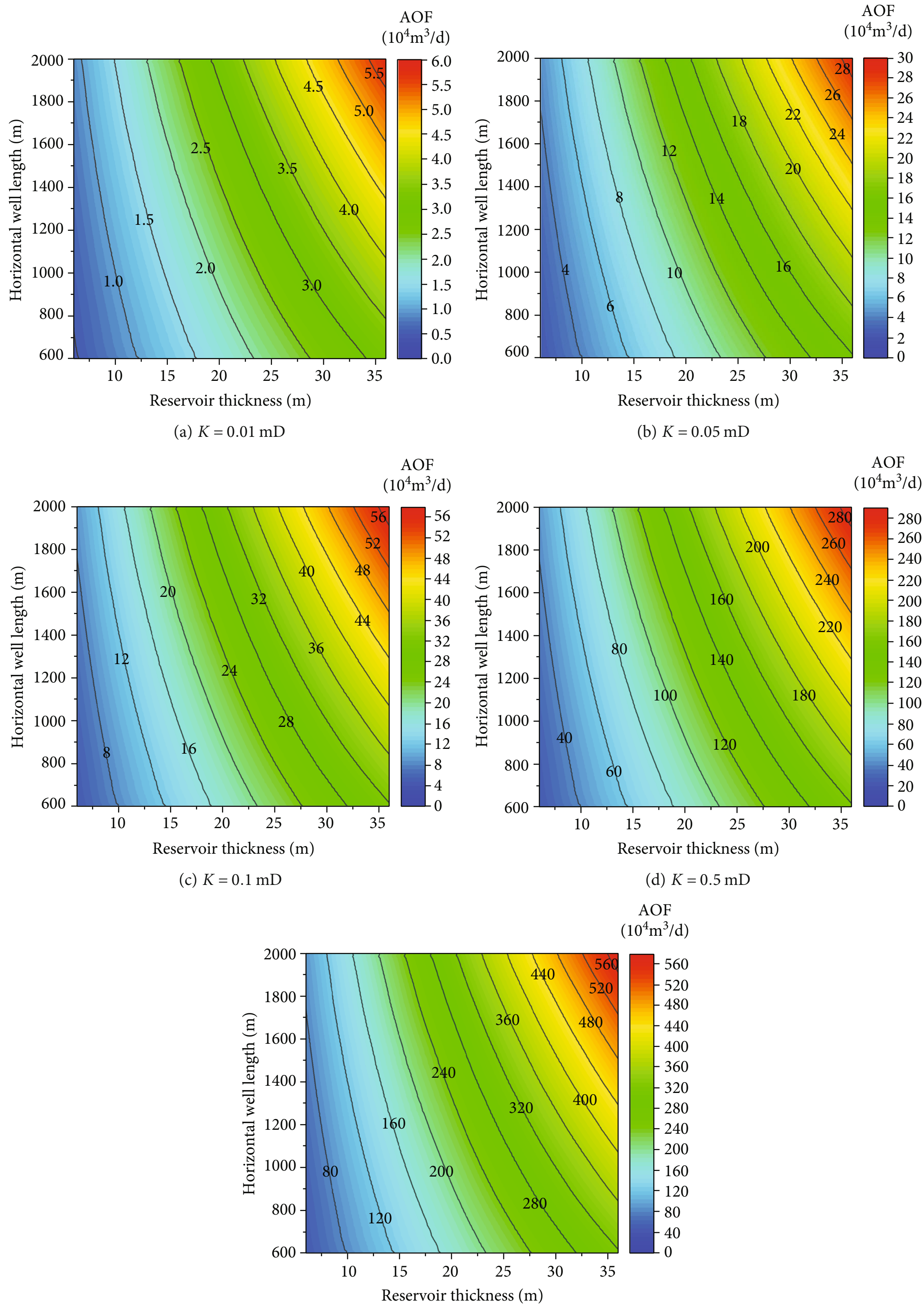


FIGURE 14: Influence of horizontal well length on MGPI.

(1) The Effect of Formation Pressure on Production Capacity. Set the formation pressure as 10, 14, 18, 22, 26, and 30 MPa, and calculate the IPR curve of the single well as shown in Figure 10. It can be seen from the figure that formation pressure has a significant impact on single well productivity. Under the same bottom-hole flowing pressure, the higher the formation pressure, the higher the single well productivity. At the same time, with the increase of production pressure difference, the difference of the single well productivity becomes more obvious. When the local formation pressure increases from 10 MPa to 30 MPa, the AOF of the single well increases from $19.58 \times 10^4\ m^3/d$ to $115.23 \times 10^4\ m^3/d$, with an increase of 4.89 times.

(2) Influence of Reservoir Thickness on Productivity. Set the formation thickness as 4~40 m, and calculate the IPR curve of the single well as shown in Figure 11. It can be seen that with the increase of reservoir thickness, the single well productivity gradually increases; besides, the increase amplitude expands gradually with the decrease of bottom-hole flowing



(a) $K = 0.01$ mD

(b) $K = 0.05$ mD

(c) $K = 0.1$ mD

(d) $K = 0.5$ mD

(e) $K = 1$ mD

FIGURE 15: Absolute open flow (AOF) chart corresponding to reservoir thickness and horizontal well length.

pressure. When the reservoir thickness increases from 4 m to 40 m, the AOF of the gas well increases from 18.55×10^4 m^3/d to 152.31×10^4 m^3/d, with an increase of 7.21 times. In addition, in order to analyze the relationship between reservoir thickness and gas productivity index per meter (MGPI) [34, 35] (surface volume of natural gas produced by unit gas reservoir thickness and unit gas drop), the MGPI corresponding to different reservoir thicknesses is calculated, and the results are shown in Figure 12. It can be found that, with the increase of reservoir thickness, the MGPI increases initially and decreases to follow. The inflection point of the curve appears at about 20 m of reservoir thickness; that is, when the reservoir thickness is 20 m, the production capacity per unit reservoir thickness is the largest. However, it should be noticed that the specific impact of reservoir thickness on the MGPI is not obvious, and it does not exceed 100 m^3/(d·MPa·m) on the range of MGPI corresponding to different reservoir thicknesses.

(3) Influence of Reservoir Permeability on Productivity. Set the reservoir permeability as 0.05~3.2 mD, and calculate the MGPI of the single well as shown in Figure 13. It can be seen from Figure 13 that the greater the reservoir permeability is, the greater the MGPI of a single well is, and the increasing trend of MGPI is fast initially and slow to follow with the increase of permeability. The increase of MGPI decreases as the reservoir permeability is greater than 1.2 mD.

4.2.3. Impact of Horizontal Well Length on Capacity. In order to analyze the impact of horizontal well length on productivity, the above relevant data are used to calculate the length of horizontal well and corresponding MGPI under different gas reservoir thicknesses. The results are shown in Figure 14. It can be seen from Figure 14 that the MGPI increases with the increase of horizontal well length, but the increase amplitude gradually decreases; at the same time, it can be seen that when the length of the horizontal section is greater than 1400 m, the increment of MGPI decreases with the increase of gas reservoir thickness. Therefore, for low-permeability gas reservoirs, with strong reservoir heterogeneity, whose reservoir thickness varies greatly, the length of horizontal wells should be controlled within 1400 m in order to improve economic benefits.

With large variation in permeability after fracturing and reforming low-permeability gas reservoirs, the influence of horizontal well length on the AOF of gas wells is calculated according to different reservoir thicknesses and permeability conditions in order to strengthen the guiding role of the conclusions in this paper for field production. The three developed horizontal wells (QL203h1, QL205h1, and QL205h2) mentioned above are used as reference wells with different permeability levels, and the results are shown in Figure 15. It shows the AOF chart of gas well corresponding to the reservoir thickness and horizontal well length when the reservoir permeability is 0.01 mD, 0.05 mD, 0.1 mD, 0.5 mD, and 1 mD, respectively, which can help to select the horizontal well length during the development of low-permeability gas reservoir. It must be mentioned that these charts were established based on three known development wells. As the exploitation continues, detailed charts applicable to different regions can be further established based on some typical wells to improve the reliability and accuracy of the recommended results.

5. Conclusion

(1) Based on the simplification of the flow zone of horizontal wells in gas reservoirs as well as the equivalent treatment of flow field splitting, combined with the stable seepage theory plus the equivalent seepage resistance method, the productivity calculation formula of horizontal wells in low-permeability gas reservoirs under the combined action of threshold pressure gradient, stress sensitivity, and slippage effect is derived. The analysis of the case indicates that the new formula is simple in calculation process, with the more practical calculation results and a deviation rate of only 8.35%, which can achieve accurate prediction of horizontal well productivity in low-permeability gas reservoirs

(2) Factors including threshold pressure gradient, stress sensitivity, and slippage effect have different degrees of influence on the productivity of horizontal wells, among which stress sensitivity has the most significant effect on production. With the decline of bottom-hole flowing pressure, the effect of stress sensitivity on productivity becomes more obvious, which greatly reduces productivity; the second is the threshold pressure gradient, making the IPR curve moving to the left as a whole, with the smaller productivity; slippage effect has the least impact, with the decline of bottom-hole flowing pressure, the impact on productivity of which gradually appears, with a trend of increasing productivity

(3) The higher the formation pressure is, the higher the single well productivity is; besides, with the increase of production pressure difference, the difference of the single well productivity is more obvious; with the increase of reservoir thickness, the single well productivity gradually increases, and the increase amplitude gradually expands with the decline of bottom-hole flowing pressure; the greater the reservoir permeability is, the greater the MGPI of a single well is. The increasing trend of MGPI with the increase of permeability is fast initially and slow to follow. The increasing range of MGPI decreases as the reservoir permeability is greater than 1.2 mD

(4) The MGPI increases with the increase of horizontal well length, but the increasing range decreases gradually; when the length of horizontal well is greater than 1400 m, the increment of MGPI decreases with the increase of gas reservoir thickness. Therefore, for low-permeability gas reservoirs, with strong reservoir heterogeneity, whose reservoir thickness varies greatly,

the length of horizontal wells should be controlled within 1400 m in order to improve economic benefits

(5) Based on this understanding, the open flow chart of gas well corresponding to the reservoir thickness and horizontal section length is given when the reservoir permeability is 0.01 mD, 0.05 mD, 0.1 mD, 0.5 mD, and 1 mD, respectively, which can help in the selection of horizontal well length during the development of low-permeability gas reservoir

Data Availability

The reservoir and production data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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