Investigation of Productivity Prediction Method for Horizontal Wells in Gas Reservoirs with Closed Bottom and Top Boundaries

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ABSTRACT: This study aims to predict the productivity of an open-hole horizontal gas well (OHHGW) in a gas reservoir with closed bottom and top boundaries (GRCBTBs). First, according to the theory of mirror imaging, an OHHGW in GRCBTBs is transformed into an infinite well array in infinite formation. Second, based on conformal transformation principle, the infinite well array is transformed into two production and two injection wells in the complex plane. Finally, according to the superposition principle of potential, a new productivity prediction method, which is suitable for the horizontal well in GRCBTBs, was developed. The field measured data of Jingbian gas field of Ordos Basin demonstrate the ability of the method to accurately predict the productivity of the OHHGW in GRCBTBs, and the prediction relative error of absolute open flow of well Longping 1 is only 1.03%, that is to say that the method proposed in this study has a certain guiding significance for the development of horizontal wells in GRCBTBs.

1. INTRODUCTION

Since the 1980s, horizontal wells have been industrialized in the United States, Canada, France, and other countries, and the research and application of horizontal well technology has been further developed.1 Horizontal wells have attracted much attention due to their advantages of large gas release area and small production pressure difference. In order to improve the development benefit of horizontal gas wells, it is important to study the productivity prediction of horizontal wells.2 At present, there are some classic research studies on horizontal well productivity at home and abroad, such as those of Borisov,3 Giger,4,5 Joshi,6,7 Renard,8 Chen,9 and Fan.10,11 The Borisov model is only applicable for homogeneous reservoirs, and the well is located in the vertical middle of the reservoir, and the fluid is incompressible;12 the applicable conditions of the Giger model are the same as those of the Borisov model, and when it is used in heterogeneous gas reservoirs, it is necessary to replace horizontal permeability with equivalent permeability.12 According to Borisov’s idea, the Joshi model decomposes the flow of the horizontal well in closed boundary reservoirs into simple addition of horizontal and vertical flows rather than vector addition, which leads to some limitations in the application of the model,13,14 and it is only suitable for gas reservoirs with small reservoir thickness.13 Chen and Renard models are derived from Joshi and Giger models, so the application conditions are the same as those of Joshi and Giger models.12,13 The models mentioned by Fan, Liu,15 and Shi16 are only suitable for bottom water gas reservoirs. To summarize, in order to improve the productivity prediction accuracy of OHHGW in GRCBTBS, transforming the production well in the closed boundaries reservoir into an infinite production well array in an infinite reservoir based on the principle of mirror image reflection, transforming the infinite well array into two production and two injection wells on the complex plane based on conformal transformation principle, and finally, a novel productivity prediction model based on the superposition principle of potential is proposed.

2. MODEL DEDUCTION

Before building the model, the following assumptions were made:

(1) The horizontal gas well is characterized by open-hole completion.
(2) The bottom and top boundaries of the reservoir are closed, and the horizontal direction is infinite stratum (Figure 1).
(3) The seepage process accords with Darcy’s law, and the effect of gravity is ignored. When the production is too
high, the non-Darcy effect is considered in the near-wellbore zone.

(4) The reservoir fluid has isothermal steady-state seepage.

(5) The porosity and permeability are constant.

The horizontal section length of the horizontal well is \( L \), the well radius is \( r_w \), the distance between the horizontal well and the lower boundary of the reservoir is \( z_w \), and the thickness of the reservoir is \( h \). According to the principle of mirror image reflection, a production well in a reservoir in which the bottom and top boundaries are closed can be transformed into an infinite well array with equal production in the infinite reservoir, as shown in Figure 2. Therefore, the \( x \) coordinates of an infinite well array are \( 2nh - z_w \) and \( 2nh + z_w \) where \( n = 0, \pm 1, \pm 2, \ldots \).

To transform the real plane (Figure 2) of an infinite production well array into a complex plane, the gas release radius of the horizontal well is \( d \) and the potential at the release radius is \( \Phi_0 \), making a straight line parallel to the \( x \) axis of the original coordinate system through the release radius, marking it as the real axis \( \eta \) of the complex plane, and then making a straight line parallel to the \( x \) axis of the original coordinate system through the original horizontal well, marking it as the imaginary axis \( \zeta \) of the complex plane; this complex plane is denoted as \( W_1 \) plane (Figure 3a). Therefore, any position in the complex plane \( W_1 \) can be expressed as

\[
W_1 = \eta + i\zeta \quad (1)
\]

By using the exponential transformation\(^{17,18}\) shown in eq 2, \( W_2 \) plane (Figure 3b) can be obtained from the \( W_1 \) complex plane.

\[
W_2 = e^{i\eta/h} \quad (2)
\]

The \( W_2 \) plane is expressed in polar coordinates as follows:

\[
W_2 = \rho e^{i\theta} \quad (3)
\]

By substituting eq 1 into eq 2, the results are

\[
\rho = e^{-\pi\zeta/h} \quad \theta = \frac{\pi\eta}{h} \quad (4)
\]

Then, the polar coordinates of the reflection wells in \( W_2 \) plane are \((e^{-\pi\zeta/h}, 0)\) and \((e^{i\pi\eta/h}, 2\pi\zeta/h)\), and the equivalent well radius is

\[
r_w^* = \frac{\pi r_w}{h} e^{-\pi d/h} \quad (5)
\]

The \( W_2 \) plane can be converted to the \( W_3 \) plane (Figure 3c) by the following transformation:

\[
W_3 = \ln W_2 = -\frac{\pi\zeta}{h} + i\frac{\pi\eta}{h} \quad (6)
\]

The coordinates of reflection wells in \( W_3 \) plane are \((-\pi d/h, 0)\) and \((\pi d/h, 2\pi\zeta/h)\).

The \( W_2 \) plane can be transformed into \( W_4 \) plane (Figure 3d) through the following transformation:

\[
W_4 = iW_3 + \frac{\pi\zeta}{h} = \frac{\pi(z_w - \eta)}{h} - i\frac{\pi\zeta}{h} \quad (7)
\]

Hence, the coordinates of the two production wells in \( W_4 \) plane are \((\pi\zeta/h, -\pi d/h)\) and \((\pi\zeta/h, \pi d/h)\).

Considering the influence of constant pressure boundary, by using mirror image reflection principle, the two production wells and two injection wells in \( W_5 \) plane (Figure 3e) are obtained. The coordinates of the two production wells in \( W_5 \) plane are \((\pi\zeta/h, -\pi d/h)\) and \((\pi\zeta/h, \pi d/h)\), and the coordinates of the two injection wells are \((\pi\zeta/h, \pi d/h)\) and \((\pi\zeta/h, -\pi d/h)\).

Let

\[
W_5 = U_5 + iV_5 \quad (8)
\]

From the fact that the real part and the imaginary part are respectively equal, we can get the following results:

\[
U_5 = \frac{\pi(z_w - \eta)}{h} \quad V_5 = -\frac{\pi\zeta}{h} \quad (9)
\]

We introduce the potential function for a gas reservoir as

\[
\Phi = 2\int_{-\pi}^{\pi} \frac{\int p}{\mu(p)Z(p)} dp \quad (10)
\]

According to Darcy’s law, under the condition of steady flow, the potential function at any point in the reservoir can be expressed as\(^{19,20}\)
temperature in standard state (K), and complex potential difference at any point M in the $W_5$ plane can be expressed as

$$\Phi = \Phi_M = \frac{T_{p_0} q_{sh}}{\pi KT_{sc}} \left[ \ln R_{e5} - \ln \left( \frac{U_5 + \frac{\pi z_w}{h}}{V_5 + \frac{\pi d}{h}} \right) \right]$$

(11)

where $P_{sc}$ is the pressure in standard state (Pa), $q_{sh}$ is the gas production per unit length under the standard condition [m$^3$/(s·m)], $K$ is the gas reservoir permeability (m$^2$), $T_{sc}$ is the temperature of gas reservoir (K), and $T$ is the gas reservoir temperature (K).

According to the superposition principle of potential, the complex potential difference at any point $M$ in the $W_5$ plane can be expressed as

$$\Phi = \Phi_M = \frac{T_{p_0} q_{sh}}{\pi KT_{sc}} \left[ \ln R_{e5} - \ln \left( \frac{U_5 + \frac{\pi z_w}{h}}{V_5 + \frac{\pi d}{h}} \right) \right] + \ln \left( \frac{2\pi d}{\pi r_w} \right)$$

(12)

where $R_{e5}$ is the supply radius in $W_5$ plane. By substituting eq 9 into 12 and simplifying it, we can get the following results:

$$\Phi = \Phi_M = \frac{T_{p_0} q_{sh}}{2\pi KT_{sc}} \left[ \ln \left( \frac{\eta^2 + (d + \zeta)^2}{\eta^2 + (d - \zeta)^2} \right) + \ln \left( \frac{(2\pi w - \eta)^2 + (d + \zeta^2)}{(2\pi w - \eta)^2 + (d - \zeta)^2} \right) \right]$$

(13)

Because of the value of $e^{(-w/d)}$ is very close to zero, so when $\eta = r_w$ and $\zeta = d$, the potential difference at the wellbore wall is

$$\Phi = \Phi_{aw} = \frac{T_{p_0} q_{sh}}{2\pi KT_{sc}} \left[ 2 \ln \frac{2\pi d}{\pi r_w} + 2\pi d \ln \frac{z_w^2 + d^2}{z_w^2} \right]$$

(14)

Considering the influence of reservoir damage near the wellbore, the potential difference can be modified as

$$\Phi = \Phi_{aw} = \frac{T_{p_0} q_{sh}}{2\pi KT_{sc}} \left[ 2 \ln \frac{2\pi d}{\pi r_w} e^{-\eta^2} + 2\pi d \ln \frac{z_w^2 + d^2}{z_w^2} \right]$$

(15)

where $S$ is the skin factor.

Therefore, the gas production under the standard condition of the horizontal well is

$$q_{sc} = \frac{1.728 \times 10^5 \pi KT_{sc}(\Phi_{aw} - \Phi_{aw})L}{TP_{p_0}}$$

(16)

where $K$ is reservoir permeability (m$^2$), $r_w$ is the well radius (m), $d$ is the gas release radius of the horizontal well (m), $h$ is the reservoir thickness (m), $q_{sc}$ is the gas production of the horizontal well (m$^3$/d), $T$ is the temperature of reservoir (K), $T_{sc}$ is the temperature of standard condition (K), $L$ is the length of the horizontal well (m), and $z_w$ is the distance from bottom boundary of reservoir to the well (m).

Because of the seepage velocity of the gas being much higher than that of the liquid, especially near the well wall, when the seepage velocity increases to a certain value, the relationship between seepage velocity and pressure gradient will no longer be linear; that is, the high-speed-non-Darcy flow effect is produced. At present, the following Reynolds number expression is often used to judge the critical seepage velocity of Darcy and non-Darcy flow:
where \( v \) is the seepage velocities \((\text{cm/s})\), \( \rho \) is the fluid density \((\text{g/cm}^3)\), \( K \) is the reservoir permeability \((\text{D})\), \( \mu \) is the fluid viscosity \((\text{mPa-s})\), and \( \phi \) is the reservoir porosity \((\text{decimal})\).

When \( r_w \) is less than or equal to 10\( r_e \), that is, in the non-Darcy region,22 and if the Reynolds number \( R_e \) is greater than 0.2, the effect of non-Darcy flow should be considered. According to the binomial seepage law of Forchheimer,23 the potential difference caused by non-Darcy can be expressed as below.

\[
\Delta \Phi_{\text{ND}} = \alpha_{\text{ND}} \left( \frac{1}{r_w} - \frac{1}{r_e} \right)
\]

(18)

\[
\alpha_{\text{ND}} = \frac{5.103 \times 10^{-11} gTq_{\text{sch}}^2}{K^{1.3} h_g^3}
\]

(19)

where \( \mu_f \) is the gas average viscosity \((\text{Pa-s})\), \( r_{\text{ND}} \) is the non-Darcy region radius \((\text{m})\), \( \gamma_g \) is the relative density of gas \((\text{decimal})\), and \( r \) is the arbitrary radius in the non-Darcy region \((\text{m})\).

When \( r_{\text{ND}} \) is equal to 10\( r_w \), eq 18 can be rewritten as follows:24

\[
\Delta \Phi_{\text{ND}} = \Delta \Phi_{\text{ed}} + \frac{1}{10r_w} = \frac{\alpha_{\text{ND}}}{r}
\]

(20)

In the complex plane \( W_1 \) (Figure 2a), the coordinates of the infinite well array can be expressed as follows:

\[
\begin{align*}
W_1 &= 2n\pi i + d \\
W_2 &= 2n\pi i + 2\pi w + id \\
&\text{where } n = 0, \pm 1, \pm 2, \ldots \pm \infty
\end{align*}
\]

(21)

Based on the superposition principle of potential, the potential difference of non-Darcy of any position \( W \) in the complex plane \( W_1 \) can be given as

\[
\Delta \Phi = \alpha_{\text{ND}} \sum_{n=-\infty}^{\infty} \left( \frac{1}{W - W_{1n}} + \frac{1}{W - W_{2n}} \right)
\]

(22)

By expanding eq 22, we can get the following results:

\[
\Delta \Phi = \alpha_{\text{ND}} \left[ \frac{1}{W - W_{01}} + \sum_{n=1}^{\infty} \left( \frac{1}{W - W_{1n}} - \frac{1}{W_{1n}} \right) + \frac{1}{W - W_{02}} + \sum_{n=1}^{\infty} \left( \frac{1}{W - W_{2n}} - \frac{1}{W_{2n}} \right) \right]
\]

(23)

By using the sum of series, the above eq 23 can be simplified as follows:

\[
\Delta \Phi = \alpha_{\text{ND}} \left[ \frac{1}{W - W_{01}} + \frac{1}{W - W_{02}} + f(W) \right]
\]

(24)

in which

\[
f(W) = \left[ \psi \left( 1 - \frac{W - W_{01}}{2h} \right) - \psi \left( \frac{W - W_{01}}{2h} + 1 \right) \right] + \psi \left( 1 - \frac{W - W_{02}}{2h} \right) - \psi \left( \frac{W - W_{02}}{2h} + 1 \right)
\]

(25)

where \( \psi(x) \) is the double gamma function.

Let

\[
Z_1 = \frac{W - W_{01}}{2h} \quad Z_2 = \frac{W - W_{02}}{2h}
\]

(26)

Then eq 24 can be further simplified as

\[
\Delta \Phi = \frac{\alpha_{\text{ND}}}{2h} \left[ \frac{1}{Z_1} + \frac{1}{Z_2} + \psi(1 - Z_1) - \psi(1 + Z_1) + \psi(1 - Z_2) + \psi(1 + Z_2) \right]
\]

(27)

Based on the reflection and transitive properties of double gamma function, the above eq 27 can be simplified as

\[
\Delta \Phi = \frac{\pi \alpha_{\text{ND}}}{2h} \left[ \cot(\pi Z_1) + \cot(\pi Z_2) \right]
\]

(28)

By using the trigonometric relation of complex numbers, the above eq 28 can be simplified as follows:

\[
\Delta \Phi = \frac{\pi \alpha_{\text{ND}}}{2h} \left[ \frac{\cos^2(x_1) + \sin^2(x_1) \tan h^2(y)}{\cos^2(x_1) \tan h^2(y) + \sin^2(x_1)} \right. \]

\[
\left. + \frac{\cos^2(x_2) + \sin^2(x_2) \tanh(y)^2}{\cos^2(x_2) \tan h^2(y) + \sin^2(x_2)} \right]
\]

(29)

\[
x_1 = 0.5\pi \eta/h \\
x_2 = 0.5\pi \eta/h - \pi \omega_w/h \\
y = 0.5\pi(\zeta - d)
\]

(30)

When point \( W \) is on the well wall, that is, \( \eta = r_w \) and \( \zeta = d \), the potential difference on the well wall can be expressed as

\[
\Delta \Phi = \frac{\pi \alpha_{\text{ND}}}{2h} \left[ \cot^2 \left( \frac{\pi \omega_w}{2h} \right) + \cot^2 \left( \frac{\pi \omega_w - 2\pi \omega_w}{2h} \right) \right]
\]

(31)

From the above eqs 20 and 31, the non-Darcy potential difference on the well wall can be expressed as

\[
\Delta \Phi_{\text{ND}} = \frac{\pi \alpha_{\text{ND}}}{2h} \left[ \cot^2 \left( \frac{\pi \omega_w}{2h} \right) + \cot^2 \left( \frac{\pi \omega_w - 2\pi \omega_w}{2h} \right) \right] - \frac{\alpha_{\text{ND}}}{10r_w}
\]

(32)

Therefore, the binomial productivity equation can be expressed as

\[
\Phi_e - \Phi_{w1} = Aq_{\text{sch}} + Bq_{\text{sch}}^{-2}
\]

(33)

in which

\[
A = \frac{\left( 2 \ln \frac{2\omega_w}{\omega_w} + \frac{2a}{k} + \ln \frac{z_2 - d}{z_2} \right)}{2\pi KT_{sc}}
\]

(34)
and

\[ B = 2.5515 \times 10^{-11} \frac{T \pi}{\mu_k k_h^4} \left[ \cot^2 \left( \frac{\pi r_w}{2h} \right) \right] \]

\[ + \sqrt{\cot^2 \left( \frac{\pi r_w - 2\pi r_e}{2h} \right) - \frac{h}{5\pi r_w}} \]  

Converting the units of all parameters in the productivity equation to the actual units used in the gas field, the binomial productivity equation of the whole horizontal well can be expressed as

\[ q_{sc} = -a + \sqrt{a^2 + 4b(\Phi - \Phi_{sf})} \]  

in which

\[ a = \frac{2 \ln \left( \frac{2b}{\pi \sigma_w e^c} + \frac{2b}{\pi} \ln \left( \frac{z^2 + 1}{z^2} \right) \right) T_{pc}}{0.1728\pi KT_{sc}} \]  

and

\[ b = \frac{1.08086 \times 10^{-10} \frac{T \pi}{\mu_k k_h^4} \left[ \cot^2 \left( \frac{\pi r_w}{2h} \right) \right] \sqrt{\cot^2 \left( \frac{\pi r_w - 2\pi r_e}{2h} \right) - \frac{h}{5\pi r_w}} \]  

where \( K \) is reservoir permeability (mD), \( \mu_g \) is the gas viscosity (mPa·s), \( r_w \) is the well radius (m), \( d \) is the gas release radius of the horizontal well (m), \( h \) is the reservoir thickness (m), \( q_{sc} \) is the gas production of the horizontal well (m³/d), \( \gamma_g \) is the relative density of gas, \( T \) is the temperature of reservoir (K), \( T_{sc} \) is the temperature of standard condition, \( T_{pc} \) is the pressure of standard condition, \( p_{sc} \) is the potential (MPa), and \( \Phi \) is the porosity.

In anisotropic reservoirs, the horizontal permeability is \( K_{h} \) and the vertical permeability is \( K_{v} \), the \( h \) and \( z \) in the productivity equation are replaced by \( h^a \) and \( z^a \), and thus the heterogeneous reservoir is transformed into a homogeneous reservoir.

\[ \begin{align*}
  h^a &= h \sqrt{\frac{K_h}{K_v}} \\
  z^a &= z \sqrt{\frac{K_h}{K_v}}
\end{align*} \]

3. RESULTS AND DISCUSSION

3.1. Model Validation. In order to validate the model proposed in this study, the basic parameters and the well test interpretation results of well Longping 1 in Jingbian gas field of Ordos Basin are used, which are shown in Tables 1 and 2.

The model proposed in this work and other related models are used for calculation; the production and relative error (r-err) results are shown in Table 3.

It can be seen from the above calculation results that the accuracy of the proposed model in this paper is much higher than that of other models which are widely used in oil reservoirs, and the accuracy meets the needs of field application, and the calculation accuracy increases with increasing production pressure difference. Therefore, the correctness of the model proposed in this work can be obtained. At the same time, it also can be seen that the other several widely used models have lost their applicability in closed bottom and top boundary gas reservoirs.

3.2. Influencing Factors Analysis. For gas wells, the productivity index in the form of pseudo pressure is defined as

\[ J = \frac{q_{sc}}{\Phi - \Phi_{sf}} \]  

So, the productivity indexes of the horizontal and vertical wells are \( J_h \) and \( J_v \) respectively.

3.2.1. Effect of Reservoir Thickness. When the horizontal well is located in the vertical middle of the reservoir, other parameters remain unchanged except for reservoir thickness; the relationship between reservoir thickness (\( h \)) and productivity index ratio of horizontal and vertical wells (\( J_h/J_v \)) is shown in Figure 4.

As can be seen from the above Figure 4, the productivity index ratio of horizontal and vertical wells decreases with increasing reservoir thickness; that is, the productivity of the horizontal well is gradually reduced and that of the vertical well is gradually increased. Therefore, the horizontal well is more suitable for the development of gas reservoirs with small thickness, whereas the vertical well is more suitable for reservoirs with larger thickness.

3.2.2. Effect of Reservoir Anisotropy. In order to study the effect of reservoir anisotropy (\( \beta \)) on horizontal well productivity, other parameters remain unchanged except for reservoir anisotropy, and the relationship between reservoir anisotropy and productivity index ratio of horizontal and vertical wells is shown in Figure 5.

As shown in the above figure, the productivity index ratio of horizontal and vertical wells decreases with increasing anisotropy factor, which is because a decrease of vertical permeability will inevitably lead to an increase of vertical seepage resistance, thus reducing the productivity of the horizontal well. On the contrary, the productivity of the horizontal well increases with decreasing anisotropy factor. It can be concluded that the horizontal well is more suitable for the reservoir with higher vertical permeability than the vertical well. This is also the reason why the horizontal well is more suitable for vertical fracture gas reservoirs.

| Table 1. Basic Parameters of Well Longping 1 |
|---------------------------------------------|
| parameter | value | parameter | value |
| temperature, K | 368.8 | pressure, MPa | 29.39 |
| thickness, m | 6.31 | length of horizontal section, m | 99.3 |
| vertical position, m | 3.155 | skin factor | 0.144 |
| horizontal permeability, mD | 9.65 | vertical permeability, mD | 7.54 |
| porosity, % | 7.77 | well radius, m | 0.0797 |
| relative density | 0.608 | supply radius, m | 144.86 |
| average viscosity, mPa·s | 0.0222197 | average deviation factor | 0.97379 |
| critical temperature, K | 200.5 | critical pressure, MPa | 4.73 |

| Table 2. Well Test Results of Well Longping 1 |
|---------------------------------------------|
| well name | \( \Delta p_1 \) | \( \Delta p_2 \) | open flow |
| Longping 1 | 5.62 MPa | 7.01 MPa | 94.6186 |

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3.2.3. Effect of Vertical Position of Well. In order to study the effect of the vertical position of the horizontal well in the reservoir on horizontal well productivity, other parameters remain unchanged except for the vertical position, and the results are shown in Figure 6.

In the reservoir with closed bottom and top boundaries, the productivity index ratio of the well increases with increasing dimensionless position \( z_w/h \); when the dimensionless position is less than 0.5, the productivity index of the horizontal well increases rapidly, whereas when the dimensionless position is greater than 0.5, the productivity index of the horizontal well increases slowly with the dimensionless position. Therefore, in the closed bottom and top boundary gas reservoir, the horizontal well should be located above the middle of the vertical thickness of the reservoir.

4. CONCLUSIONS

According to the image reflection theory, conformal transformation theory, and superposition principle of potential function, a new productivity prediction model of horizontal well completion with open hole in the gas reservoir in which the bottom and top boundaries are closed is proposed. The model is verified by measuring the data of the horizontal well in Jingbian gas field, and the results show that the proposed model can well predict the productivity of a horizontal well in closed bottom and top boundaries gas reservoirs. The prediction relative error of absolute open flow of well Longping 1 is only 1.03%, and hence, it can be concluded that the model proposed in this work is reliable, and it can provide theoretical guidance for the development of horizontal wells in closed bottom and top boundary gas reservoirs.

The factor analysis results show that the horizontal well is more suitable for the development of gas reservoirs with small reservoir thickness and the vertical well is more suitable for gas reservoirs with larger thickness; the horizontal well is more suitable for the development of reservoirs with high vertical permeability; and the horizontal well should be located above the middle of vertical thickness in gas reservoirs in which the bottom and top boundaries are closed.

| model  | \( \Delta p_1 = 5.62 \) | r-err | \( \Delta p_2 = 7.01 \) | r-err | open flow | r-err (%) |
|--------|-----------------|------|-----------------|------|-----------|---------|
| this work | 32.474 | 7.22 | 39.403 | 1.49 | 93.6412 | 1.03 |
| Joshi  | 51.665 | 47.61 | 60.127 | 50.32 | 125.4092 | 32.54 |
| Chen   | 51.764 | 47.90 | 60.232 | 50.58 | 125.5432 | 32.68 |
| Borisov | 54.257 | 55.02 | 62.884 | 57.21 | 128.8733 | 36.20 |
| Giger  | 47.907 | 36.88 | 55.817 | 39.54 | 116.9943 | 23.65 |

Figure 4. Influence of \( h \) on \( J_h/J_v \).

Figure 5. Influence of \( \beta = (K_h/K_v)^{0.5} \) on \( J_h/J_v \).

Table 3. Horizontal Well Production Calculated by Different Models

Figure 6. Influence of \( z_w/h \) on the productivity index of a horizontal well.

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Notes
The authors declare no competing financial interest.

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