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Productivity Evaluation of Radial Multi-Branch Horizontal Well in Unconventional Gas Reservoirs Considering Permeability Variation: Model Establishment and Sensitivity Analyses

Juntai Shi, Yexin Fang, Jiayi Wu, and Zheng Sun, China University of Petroleum Beijing; Jizhou Tang, Harvard University; Qian Li, Research Institute of Petroleum Exploration and Development in PetroChina Southwest Oil & Gas Field Company; Zan Chen, Sinopec Petroleum Exploration and Production Research Institute; Jiaguo Lu, China University of Petroleum Beijing; Wenqi Ke, Sinopec Petroleum Exploration and Production Research Institute; Yanran Jia, China University of Petroleum Beijing; Yabing Wang, PetroChina Huabei Oilfield Company Erlian Branch Hanan oil production area; Wenming Lu, Sinopec Petroleum Exploration and Production Research Institute

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Abstract

The low permeability of unconventional gas reservoir makes it difficult to achieve good development effect. Hydraulic fracturing technology and multi-lateral well technology are usually adopted to increase the gas production. What's more, the permeability may change dynamically during the production process because of the effective stress, gas slippage and matrix shrinkage effect.

In this paper, we first establish the productivity equation of radial multi-branch horizontal (RMBH) well in unconventional natural gas reservoirs, considering the dynamic change of permeability during the production process. Then, the productivity equation of radial horizontal well with 2 branches is compared with fractured vertical well and conventional horizontal well productivity equations proposed by former researchers. Finally, main factors influencing the productivity of unconventional natural gas RMBH well are analyzed, including well structure parameters, gas formation properties and production stage.

Results show that the productivity equation of degenerated RMBH well with 2 branches is proven to be reasonable by comparison with those of vertically fractured well and horizontal well. RMBH well shows more advantage in the formation with relatively large difference between maximum and minimum stresses, indicating that this type of well configuration may be an alternative technique for improving gas production in unconventional gas reservoirs. Sensitivity analyses demonstrate that the gas production rate of RMBH well is sensitive to branch length, branch number, build-up section horizontal distance, and stress dependence effect. The radial horizontal well with 4 branches can achieve a best development effect and economical benefit.

Keywords: unconventional gas reservoir, productivity equation, radial multi-branch horizontal well, dynamic permeability

Introduction

The rapid development of unconventional natural gas has attracted more and more concerns over the past decades. The low permeability of unconventional gas reservoir makes it difficult to achieve a good development effect with conventional vertical wells, so certain stimulation techniques should be adopted. What's more, the permeability of these unconventional gas reservoirs may change dynamically during the production process owing to the influences of effective stress, gas slippage, and matrix shrinkage for sorbed gas reservoirs. Thus, the productivity prediction of unconventional gas reservoirs is of vital importance considering the dynamic permeability and the stimulation methods (Chu et al., 2011; Qiao et al., 2018).

In recent years, the investigations on gas well productivity prediction have made a great progress, five mostly used methods are proposed and introduced to predict the dynamic performance of unconventional gas wells, including numerical simulation methods (Sawyer et al., 1990; Kohler and Ertekin, 1995), analytical methods (Clarkson and Qanbari, 2015; Shi et al., 2018), material balance methods (Schilthuis,1936; King and Ertekin, 1989; King, 1990) and statistical methods (Rawlins and Schellhardt, 1936; Lv et al., 2011). Among these methods, numerical simulation methods show a highly superiority for complicated heterogeneous reservoirs, but it requires relatively high time and manpower cost. Analytical methods, which are derived through rigid theoretical analyses, are very instant to forecast the dynamic performance of gas wells only using their productivity equations, and can be used to investigate the sensitivity of influencing factors on gas productivity. However, the assumptions of the analytical models may be simplified. Material balance methods can accurately predict the cumulative gas production and daily gas production rate at a given average reservoir pressure for volumetric gas reservoirs, but the results predicted by these methods may deviate the realities of unconventional gas reservoirs with water influx. Statistical methods which are generated from data fitting on some given oil and gas fields are very convenient to forecast the deliverability of gas wells, but may result in a large error for other gas reservoirs with different formation and fluid properties. In addition, statistical methods are lack of theretical basis.

Compared with conventional natural gas reservoirs, unconventional natural gas reservoirs have unique seepage mechanism and production strategy, which greatly increase the difficulty of well productivity prediction. (Zhang et al., 2018; Wang et al., 2018; Sun et al., 2019; Zhang et al., 2019). Stress sensitivity universally exists and its effect is obvious during the production of unconventional gas because of low permeability formation and natural fracture network (Morrow et al., 1984; Shi et al., 2014, 2019). Gas slippage effect is more prominent at the condition of lower pressure corresponding to the late stage of gas production (Klinkenberg, 1941; Shi et al., 2014). Matrix shrinkage effect is resulted from the adsorption phenomenon appearing in coalbed methane (CBM) reservoirs and shale gas reservoirs (Gray, 1987). Most gas exists in adsorbed state in CBM reservoirs, the matrix shrinkage effect for CBM reservoirs is more significant (Sawyer et al., 1990; Harpalani and Schraufnagel, 1990; Palmer, 1996). In order to accurately predict the dynaimic performance of unconventional gas wells, the effects of effective stress and gas slippage should be taken into consideration. In addition, the matrix shrinkage effect should be also considered for coalbed methane and shale gas reservoirs.

Currently, the stimulation methods for improving gas productivity of unconventional gas reservoirs include fracturing technology, multi-lateral well technology, acidizing, cavern completion, and so on (Liu et al., 2018; Lyu et al., 2019; Li et al., 2016; Jiang et al., 2009). Fracturing technology is widespread used in the development of shale gas, tight gas, and coalbed methane reservoirs in China, and good development effects have been achieved (Agrawal and Sharma, 2015). However, for some given unconventional gas reservoirs with large difference between maximum and minimum horizontal stresses, complex fracture networks are not easily generated, its stimulation effect and the improvement of gas well productivity are limited (Hou et al., 2018). Multi-branch well technology has been applied for increasing gas well productivity in some tight gas reservoirs and CBM reservoirs in China (Chen et al., 2012). Radial multi-branch horizontal (RMBH) well refers to the well with multiple horizontal wellbores drilled along different radial directions, which can maximize the communication with reservoir natural fractures and reduce fluid seepage resistance. The productivity equations of RMBH wells are quite different from those of conventional vertical wells and horizontal wells because of the special well structure of RMBH wells.

Productivity equations for different multi-branch horizontal wells have been established. Joshi (1988) derived a productivity equation of the side-drilled horizontal well in a homogeneous and isotropic reservoir by equivalently replacing side-drilled horizontal well with a vertical fracture with infinite conductivity. Lang et al. (1993) established a productivity equation of multi-horizontal wells in different layers using the pseudo-three-dimensional method and the equivalent seepage resistance method. Cheng and Li (1998) proposed a method for evaluating horizontal well productivity using the format of productivity equation of vertical wells. Jiang (2000) transformed the three-dimensional seepage problem into two two-dimensional problems, transformed the multi-branch horizontal wells into a unit circle by conformal transformation, and finally derived a productivity equation of multi-branch horizontal well. Qi (2009) proposed a productivity equation for a radial multi-branch horizontal well on the basis of complex function. Qi et al. (2010) further derived the pseudo-three-dimensional productivity equations for two-branch horizontal wells in strip reservoirs. Chen (2014) pointed out that the productivity equation proposed by Qi (2009) is theoretically the most complete and accurate pseudo-three-dimensional productivity equation. However, the above mensioned productivity equations of multi-branch horizontal well didn't consider the permeability variation of unconventional natural gas reservoirs.

In this work, the productivity equations for RMBH well considering permeabiliy variation in unconventional gas reservoirs are established combining the productivity equation of RMBH well proposed by Qi (2009) and the dynamic permeability model. The proposed productivity equations for RMBH well considering permeabiliy variation are compared with those for vertically fractured well and horizontal well. Finally, taking a CBM reservoir for instance, the influencing factors on gas well productivity are analyzed, and the most sensitive factors are determined, which helps engineers design the specific well structure of RMBH well to develop unconventional gas reservoirs.

Productivity equation for RMBH well in unconventional gas reservoirs

Physical model and assumptions

The physical model of radial horizontal well with three branches, a typical RMBH well, is demonstrated in Figure 1 from both top view and 3D view. There exists a relatively short build-up section between the vertical wellbore and the heel of the horizontal wellbore, and the horizontal section can be called as the effective branch. In order to establish productivity equation of RMBH well in unconventional gas reservoirs, the following assumptions are made:

1. A circular reservoir is considered and the formation is horizontal, homogeneous, and of uniform thickness.
2. The productivity of the build-up section is ignored, and the effective branches of RMBH well keep horizontal to the layer.
3. Reservoir temperature remains constant.
4. During the gas production, water volume factor is unchanged.
5. The radius of outer boundary is far larger than the length of effective branch.

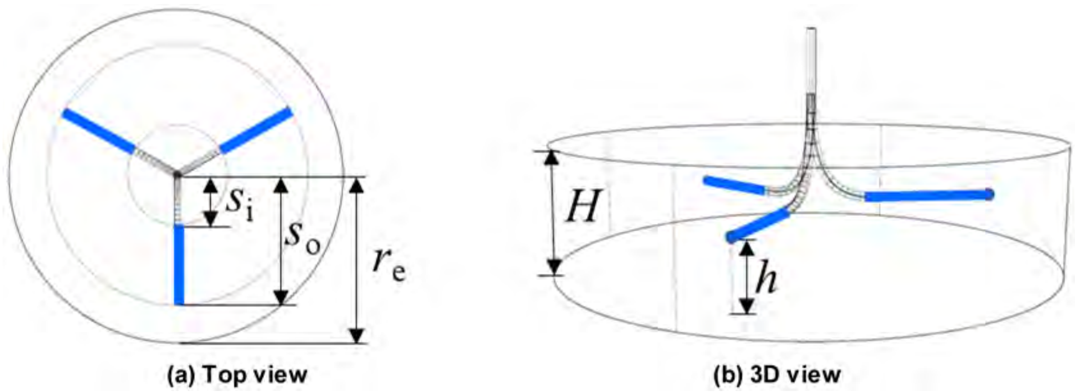


Figure 1—Schematic Diagram of RMBH well

Mathematical model establishment

During the production of unconventional natural gas reservoir, stress sensitivity, matrix shrinkage, and slippage effect can influence the productivity significantly and can not be ignored in reality. On the basis of productivity equation of oil RMBH well (Qi, 2009), considering the complexity of unconventional natural gas production process, the productivity equation of unconventional natural gas RMBH well is built.

Since there is a build-up section between the vertical wellbore and the heel of the horizontal wellbore, the complex potential (W) function, which is different from classic potential function, can be described as (Qi, 2009)

$$W = \frac{q}{\pi} \operatorname{arch} \sqrt{\left(r_e^n - s_i^n\right) / \left(s_o^n - s_i^n\right)} \tag{1}$$

where, q is the liquid flow rate per unit thickness of each branch, cm2/s; re is radius of outer boundary, m; n is the number of branches, dimensionless; si is build-up section horizontal distance, m; so is distance between main wellbore and horizontal wellbore toe, m.

Based on the productivity equation of oil, the productivity equation of RMBH well producing water or gas can be described by the same equation, which is expressed as,

$$Q = \frac{n\pi H \int_{\Phi_w}^{\Phi_e} \frac{1}{B_r} \mathrm{d}\Phi}{\operatorname{arch} \sqrt{\frac{r_e^n - s_i^n}{s_o^n - s_i^n}} + \frac{\beta H}{2\left(s_o - s_i\right)} \ln \frac{\beta H \csc\left(\pi h / H\right)}{\left(1+\beta\right) r_w}} \tag{2}$$

where, Q is the fluid flow rate of the RMBH well, cm3/s; H is the formation thickness, cm; Φ is the potential function, which is defined as the ratio of permeability to viscosity multiplied by pressure, D·atm/(mPa·s); Φe is the potential at the outer boundary, D·atm/(mPa·s);Φw is the potential at the bottom-hole, D·atm/(mPa·s); Br is the volume factor of the fluid r, cm3/scm3; β is ratio of vertical permeability to horizontal permeability, dimensionless; h is the height of horizontal branch, cm; rw is wellbore radius, cm.

Dynamic permeability is essential to productivity prediction. And the dynamic permeability considering stress sensitivity effect and matrix shrinkage effect can be expressed as (Shi, et al., 2019)

$$K = K_i \left[e^{c_p\left(p - p_e\right)} + \alpha C_a \left(\frac{p_d}{p_d + p_L} - \frac{p}{p + p_L} \right) \right]^3 \tag{3}$$

where,

$$C_a = \frac{2\nu\varepsilon_{max}}{1 + 2\nu} \tag{4}$$

$$\alpha = \begin{cases} 0 & p \geq p_d \\ 1 & p < p_d \end{cases} \tag{5}$$

where, K is dynamic permeability, mD; Ki is initial permeability, mD; C_p is pore compressibility, MPa^{-1}; p is the current reservoir pressure, MPa; p_e is the boundary pressure, MPa; C_a is matrix shrinkage factor, dimensionless; α is determination factor of matrix shrinkage effect, dimensionless; pd is critical desorption pressure, MPa; p_L is Langmuir pressure, MPa; v is Poison ratio, dimensionless; ε_{max} is ratio of decreased volume after desorption and initial volume, dimensionless.

Klinkenberg's theory of improving apparent permeability by adding a pressure relevant coefficient into expression is widely accepted. Since Klinkenberg correction mainly works under low pressure, it will only be used in the late stage of production. Then the dynamic permeability further considering Klinkenberg effect is:

$$K' = K_i\left[e^{c_p(p-p_e)} + \alpha C_a\left(\frac{p_d}{p_d+p_L} - \frac{p}{p+p_L}\right)\right]^3 \cdot \left(1+\frac{b}{p}\right) \tag{6}$$

where, b is the slippage coefficient, a parameter determined through experiments, MPa.

Note that the effect of matrix shrinkage does not exist in tight gas reservoirs, so C_a can be set as zero in the whole production process of tight gas.

Water productivity model in unconventional gas reservoirs. For water production of unconventional natural gas wells, water volume factor remains constant. Converting Darcy units to field units of Eq. (2), the water productivity equation can be written as:

$$Q_w = \frac{0.2715 nH \frac{1}{B_w}\int_{\Phi_w}^{\Phi_e} d\Phi}{\operatorname{arch}\sqrt{\frac{r_e^n - S_i^n}{S_o^n - S_i^n}} + \frac{\beta H}{2(S_o - S_i)}\ln\frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w}} \tag{7}$$

where, Q_w is the water flow rate of the RMBH well, m^3/d; H is the formation thickness, m; Φ is the potential function, mD·MPa/(mPa·s); Φ_e is the potential at the outer boundary, mD·MPa/(mPa·s); Φ_w is the potential at the bottom-hole, mD·MPa/(mPa·s); Bw is the water volume factor, m^3/sm^3; β is ratio of vertical permeability to horizontal permeability, dimensionless; h is the height of horizontal branch, m; rw is wellbore radius, m.

Apply the definition of potential function to Eq. (7), we can get the water productivity equation for unconventional gas wells:

$$Q_w = \begin{cases} \dfrac{0.2715 nK_{rw}H\frac{1}{B_w\mu_w}\int_{p_w}^{p_e} K_{\alpha=0}\,dp}{\operatorname{arch}\sqrt{\frac{r_e^n - S_i^n}{S_o^n - S_i^n}} + \frac{\beta H}{2(S_o - S_i)}\ln\frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w}}, & p \ge p_d \\[2ex] \dfrac{0.2715 nK_{rw}H\frac{1}{B_w\mu_w}\left(\int_{p_w}^{p_d} K_{\alpha=1}\,dp + \int_{p_d}^{p_e} K_{\alpha=0}\,dp\right)}{\operatorname{arch}\sqrt{\frac{r_e^n - S_i^n}{S_o^n - S_i^n}} + \frac{\beta H}{2(S_o - S_i)}\ln\frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w}}, & p < p_d \end{cases} \tag{8}$$

where, K_{rw} is water relative permeability, dimensionless; μ_w is water viscosity, mPa·s.

Since Klinkenberg effect does not exist in water production, combine Eq. (3) and Eq. (8), we can get the water productivity of RMBH well in unconventional reservoirs considering the dynamic change of permeability. With the mathematical integration method, water productivity equation of unconventional reservoir RMBH well can be calculated.

Gas productivity model in unconventional gas reservoirs. The gas volume factor is defined as

$$B_g = \frac{p_{sc} Z T}{p Z_{sc} T_{sc}} \tag{9}$$

where, B_g is the gas volume factor, m³/sm³; $p$sc is standard pressure, MPa; Z and Z_{sc} are deviation factor at current conditions and standard conditions, respectivity, dimensionless; T and T_{sc} are the current and standard reservoir temperature, respectivity, K.

Substituting Eq. (9) into Eq. (2) yields the gas productivity equation:

$$Q_g = \frac{n\pi H \int_{\Phi_w}^{\Phi_e} \frac{1}{B_g} \mathrm{d}\Phi}{\mathrm{arch}\sqrt{\frac{r_e^n - s_i^n}{s_o^n - s_i^n}} + \frac{\beta H}{2(s_o - s_i)} \ln \frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w}} \tag{10}$$

where, Q_g is the gas flow rate of the RMBH well, m3/d; B_g is the gas volume factor, m³/sm³.

For shale gas and coalbed methane reservoirs, when pressure decreases under desorption pressure, matrix shrinkage effect starts influencing permeability. Gas productivity equation can be written as:

$$Q_g = \begin{cases} \dfrac{774.6n\dfrac{K_{rg}}{T} H \displaystyle\int_{p_w}^{p_e} \frac{pK'_{\alpha=0}}{\mu_g Z} \mathrm{d}p}{\mathrm{arch}\sqrt{\frac{r_e^n - s_i^n}{s_o^n - s_i^n}} + \frac{\beta H}{2(s_o - s_i)} \ln \frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w}}, & p \geq p_d \\[2ex] \dfrac{774.6n\dfrac{K_{rg}}{T} H \left(\displaystyle\int_{p_w}^{p_d} \frac{pK'_{\alpha=1}}{\mu_g Z} \mathrm{d}p + \int_{p_d}^{p_e} \frac{pK'_{\alpha=0}}{\mu_g Z} \mathrm{d}p \right)}{\mathrm{arch}\sqrt{\frac{r_e^n - s_i^n}{s_o^n - s_i^n}} + \frac{\beta H}{2(s_o - s_i)} \ln \frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w}}, & p < p_d \end{cases} \tag{11}$$

where, K_{rg} is gas relative permeability, dimensionless; μ_g is gas viscosity, mPa·s.

Comparsions and dissicussions

Seepage resistance calculated by different productivity equations. In order to prove the rationality of RMBH well productivity equation, the seepage resistances of horizontal well, fractured vertical well, and RMBH well are calculated. If the results are basically equal, the RMBH well productivity equation can be considered to be accurate.

The radial horizontal well of 2 branches can be regarded as a special horizontal well, and its external seepage resistance can be compared with the whole seepage resistance of a vertically fractured well, thus, in this case, we validate the proposed model using the radial horizontal well of 2 branches. First, we calculate the seepage resistance of RMBH well, conventional horizontal well, and hydraulic fractured well using different productivity equations. Then, the calculation results can be compared.

The following seepage resistance calculation formula are introduced.

1. Joshi's horizontal well (1988):

$$R_J = \ln\left[\left(a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2}\right) \Big/ \frac{L}{2}\right] + (H/L)\ln[H/(2\pi r_w)] \tag{12}$$

$$a = (L/2)\left[0.5 + \sqrt{(2r_e/L)^4 + 0.25}\right]^{0.5} \tag{13}$$

   where, L is the length of horizontal well, m.

2. Lang's multi-branch well (1993):

$$R_L = \ln\frac{4^{\frac{1}{n}} r_e}{L_B} + \frac{\beta H}{nL_B} \ln \frac{\beta H \csc(\pi h/H)}{(1+\beta) r_w} \tag{14}$$

   where, L_B is the length of branch, m.

3. Vertically fractured well:

$$R_{\mathrm{F}} = \ln\left[\frac{R_{\mathrm{a}}}{L_{\mathrm{f}}} + \sqrt{\left(\frac{R_{\mathrm{a}}}{L_{\mathrm{f}}}\right)^2 - 1}\right] \tag{15}$$

where, R_a is the pressure spread distance parallel to fractures, m; L_f is hydraulic fracture half-length, m.

Table 1 shows basic parameters for the calculation of whole and external seepage resistance. Table 2 shows the results of the whole and external seepage resistance of the four well types. It can be seen that the external resistance calculated by the RMBH model has little difference with that of vertically fractured well; the whole seepage resistance calculated by the RMBH model, Joshi's model, and Lang's model are almost the same. Hence, the RMBH productivity model is rational and accuracte.

Table 1—Basic parameters for the calculation of whole and external seepage resistance

Productivity equation	Parameter	Unit	Value
Joshi's	L	m	100
	H	m	6
	r_e	m	225
	r_w	m	0.1
Lang's	r_e	m	225
	L_B	m	50
	ב	-	1
	H	m	6
	h	m	3
Vertically fractured	R_a	m	225
	L_f	m	50
RMBH	so	m	50
	s_i	m	0
	n	-	2
	h	m	3
	H	m	6
	β	-	1
	r_e	m	225
	r_w	m	0.1

Table 2—Comparation of the whole and external seepage resistance

Type of resistance	Productivity equation			
	Joshi's	Lang's	Vertically fractured	RMBH
External	2.1973	2.1972	2.1846	2.1846
Whole	2.3326	2.2425	2.1846	2.2299

Through the above calculation, the radial horizontal well with 2 branches can be indeed regarded as a horizontal well or a vertically fractured well adding an inner resistance. Considering that formation with relatively large difference between maximum stress and minimum stress cannot generate complex fracture network easily, so the RMBH well shows more advantage than vertically fractured well.

Productivity of RMBH well and vertically fractured well. Except for multi-branch well, vertically fractured well is the most used in unconventional natural gas reservoirs. The gas productivity equation of vertically fractured well can be written as:

$$Q_{\mathrm{g,vf}}=\frac{774.6H\frac{K_{\mathrm{rg}}}{T}\int_{p_{\mathrm{w}}}^{p_{\mathrm{e}}}\frac{2pK}{\mu_{\mathrm{g}}Z}\mathrm{d}p}{\ln\left[\frac{R_{\mathrm{a}}}{L_{\mathrm{f}}}+\sqrt{\left(\frac{R_{\mathrm{a}}}{L_{\mathrm{f}}}\right)^{2}-1}\right]} \tag{16}$$

where, $Q_{\mathrm{g,vf}}$ is the gas production rate of the vertically fractured well, m^3/d.

Here, productivity index ratio (*PIR*) is introduced to evaluate the relative production increase effect of RMBH well comparing to vertically fractured well. And it is defined as ratio of the productivity indices of the two type of wells. Assuming pressure at the endpoint of hydraulic fracture is equal to pressure at the bottomhole of each branch, so the formula of *PIR* can be written as:

$$PIR=\frac{n\ln\left[\frac{R_{\mathrm{a}}}{L_{\mathrm{f}}}+\sqrt{\left(\frac{R_{\mathrm{a}}}{L_{\mathrm{f}}}\right)^{2}-1}\right]}{2\mathrm{arch}\sqrt{\frac{r_{\mathrm{e}}^{n}-s_{\mathrm{i}}^{n}}{s_{\mathrm{o}}^{n}-s_{\mathrm{i}}^{n}}}+\frac{\beta H}{(s_{\mathrm{o}}-s_{\mathrm{i}})}\ln\frac{\beta H\csc(\pi h/H)}{(1+\beta)r_{\mathrm{w}}}} \tag{17}$$

On the assumption that both vertical fracture and radial branch have the same exposed area in reservoir, the following formula can be obtained:

$$2L_{\mathrm{f}}H\cdot 2=n\cdot 2\pi r_{\mathrm{w}}\cdot(s_{\mathrm{o}}-s_{\mathrm{i}}) \tag{18}$$

So, the effective branch length can be written as

$$s_{o}-s_{\mathrm{i}}=\frac{2L_{\mathrm{f}}H}{n\cdot\pi r_{\mathrm{w}}} \tag{19}$$

Then, *PIR* can be calculated with certain valves of branch number and fracture half length. As shown in Figure 2, *PIR* increases with increasing hydraulic fracture half-length, while it decreases with the increase of branch number. The values of productibity index ratio are lager than 1, demonstrating that the RMBH well is superior to vertically fractured well. What's more, the radius horizontal well with four branches has more advantage when comparing to a vertically fractured well with relatively long fracture half-length.

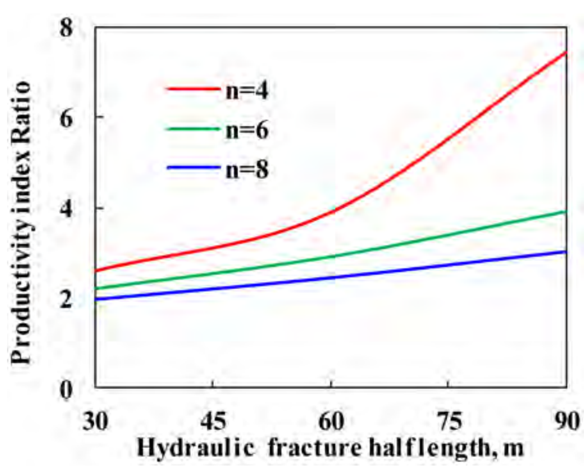
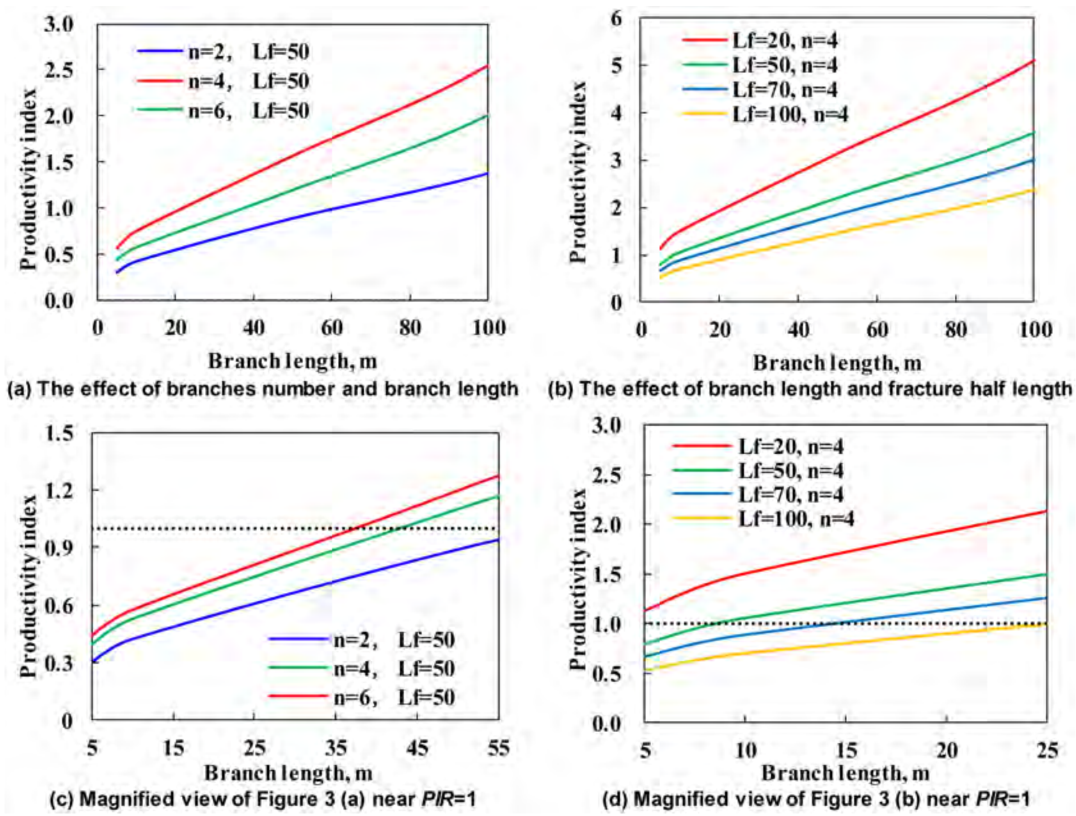


Figure 2—The comparison of *PIR* values with different branch number and hydraulic fracture half-length

It is noted that the effective branch length calculated by Eq.(18) may be quite long in some situations, which means that the conversion relationship of effective branch length, number of branches, and half-length is more suitable for reservoir with relatively large outer boundary. Thus, we further calculate the values of *PIR* under different fracture half-length, branch length, and number of branches directly using Eq. (17), which are shown in Figure (3). It can be seen that the value of *PIR* is lower than 1 when the branch length is small, meaning vertically fractured well performs better than RMBH well. In case that the half-length of fractured vertical well is a constant (Figure 3(a) and Figure 3(c)), the more branches a radial multi-branch horizontal well has, the larger *PIR* is. As for the case with the same number of branches, the value of *PIR* decreases with increasing L_f.



(a) The effect of branches number and branch length (b) The effect of branch length and fracture half length
(c) Magnified view of Figure 3 (a) near *PIR*=1 (d) Magnified view of Figure 3 (b) near *PIR*=1

Figure 3—The comparison of PIR values among different branch numbers, branch length, and hydraulic fracture half-length

Sensitivity analyses

Unconventional natural gas production mechanism is influenced by many factors. In order to investigate the extent of each influencing factor on productivity, a sensitivity analysis on the case of productivity equation of coalbed methane well is performed. The reservoir and fluid parameters of the base case are illustrated in Table 3.

Table 3—Basic reservoir and fluid parameters for sensitivity analyses

Parameter	Unit	Value	Parameter	Unit	Value
*p*e	MPa	6.3	s_o	m	105
μ_w	mPa·s	1	n	-	3
μ_g	mPa·s	0.027	K_i	mD	0.1
B_w	m^3/sm^3	1	Cp	MPa^{-1}	0.01
H	m	6	C_a	dimensionless	0.015
h	m	3	*p*d	MPa	5.6
r_e	m	225	p_L	MPa	2.5

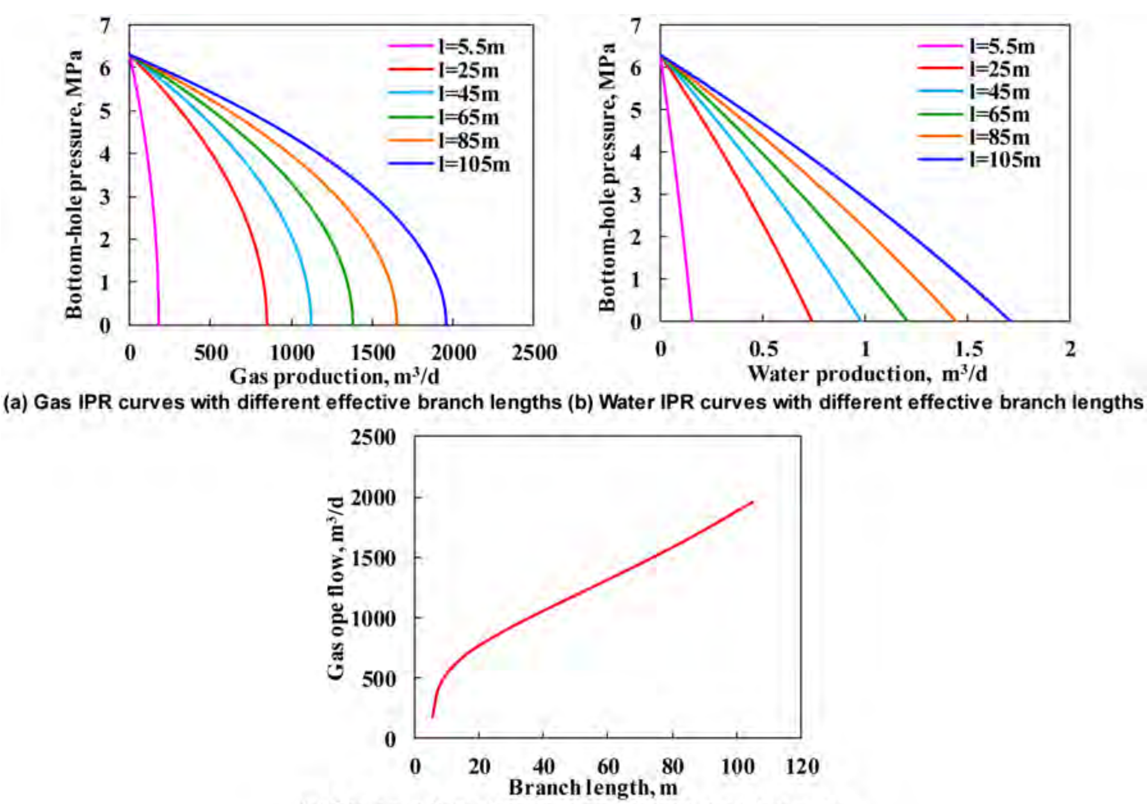
Parameter	Unit	Value	Parameter	Unit	Value
r_w	m	0.1	v	dimensionless	0.3
s_i	m	5	ε_{max}	dimensionless	0.1

The effect of the well structure parameters

The well structure of RMBH well significantly influences the well productivity. In order to design such a well with proper structure parameters, figuring out how each parameter alters the final production is necessary.

The effect of effective branch length. To analyze the effect of effective branch length, we keep the starting point of each branch invariable, i.e., the build-up section horizontal distance s_i is constant. Different distances between main wellbore and horizontal wellbore toe s_o are considered. As the productivity cannot be determined by equation because of the distortion phenomenon when the branch extended close to the outer boundary, the influence of effective branch length should be analyzed within a reasonable range.

Figure 4 shows the variation of gas and water productivities with changing the effective branch length. It shows that with the increase of effective branch length, the open flow of gas and water increase. Besides, the increase rate of gas open flow decreases. This is because the production is determined by the actual control area, and the longer effective branch has the larger control area.

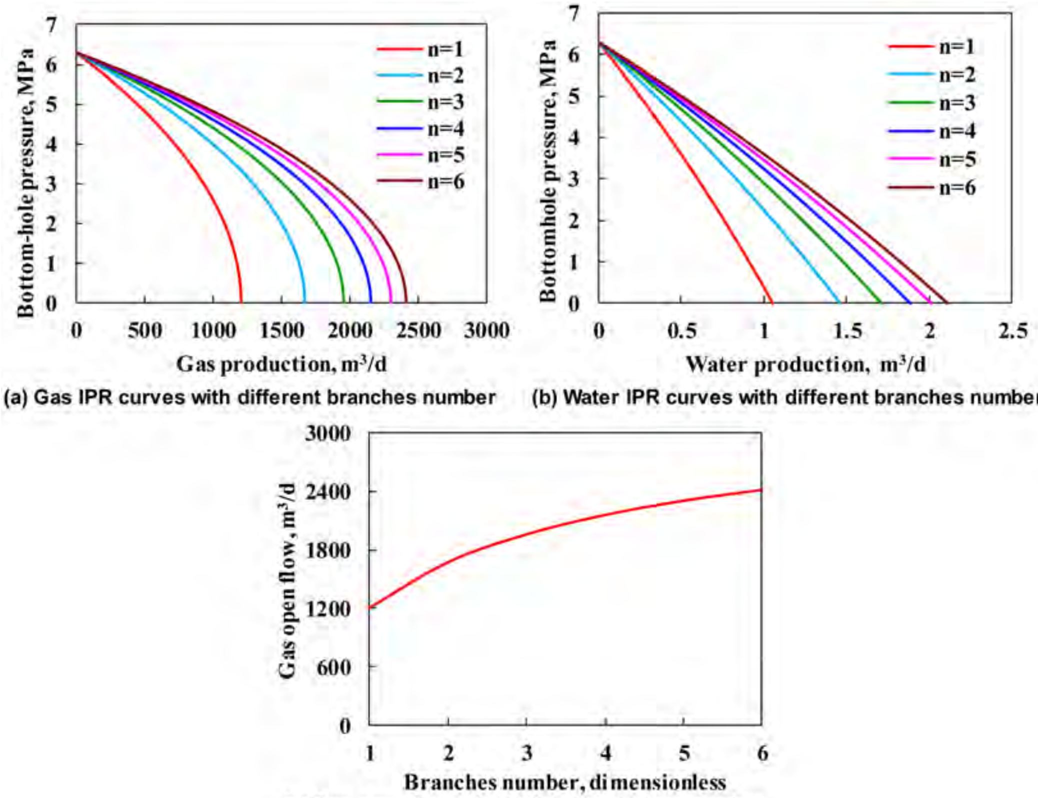


(a) Gas IPR curves with different effective branch lengths (b) Water IPR curves with different effective branch lengths

(c) Gas open flow with different effective branch lengths

Figure 4—Gas and water IPR curves and gas open flow with different effective branch lengths

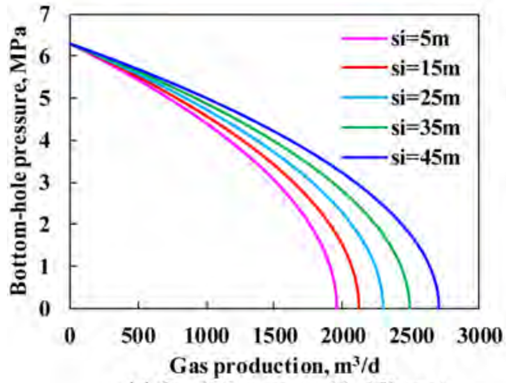
The effect of branch number. Figure 5 shows the changes of gas and water productivities with different branches number. It can be seen that when the number of branches is too small, the productivity is low. Although the productivity has been significantly improved with many branches, the growth rate of productivity is gradually reduced due to the interaction between each branch. From the perspective of development and economy, there is a most reasonable branches number (around 4), which can guide the determination of branches number of radial horizontal wells.



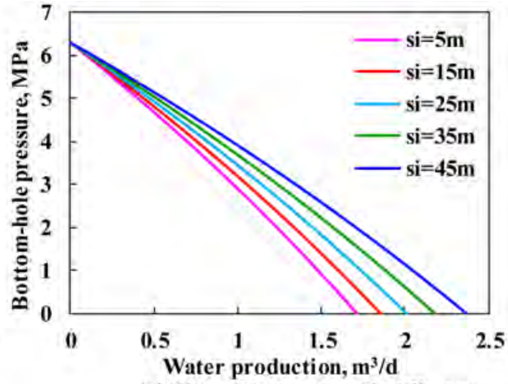
(a) Gas IPR curves with different branches number
(b) Water IPR curves with different branches number
(c) Gas open flow with different branches number

Figure 5—Gas and water IPR curves and gas open flow with different branches number

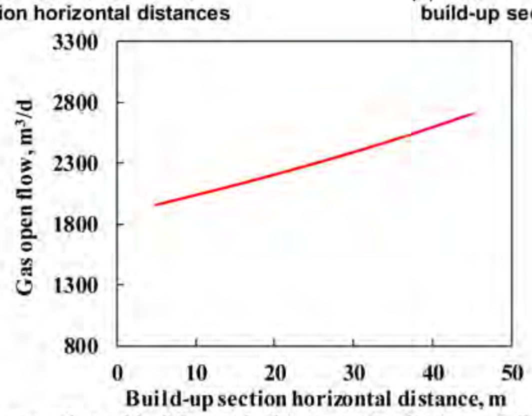
The effect of build-up section horizontal distance. Figure 6 shows the variation of gas and water productivity with different build-up section horizontal distance. The further away the effective branches are from the vertical main wellbore, the less influence they have on each other and the greater control area of RMBH well is. As Figure 6 shows, productivity increases with the increase of build-up section horizontal distance. The optimum build-up section horizontal distance can be determined combing with the economic factors and boundary conditions.



(a) Gas IPR curves with different build-up section horizontal distances



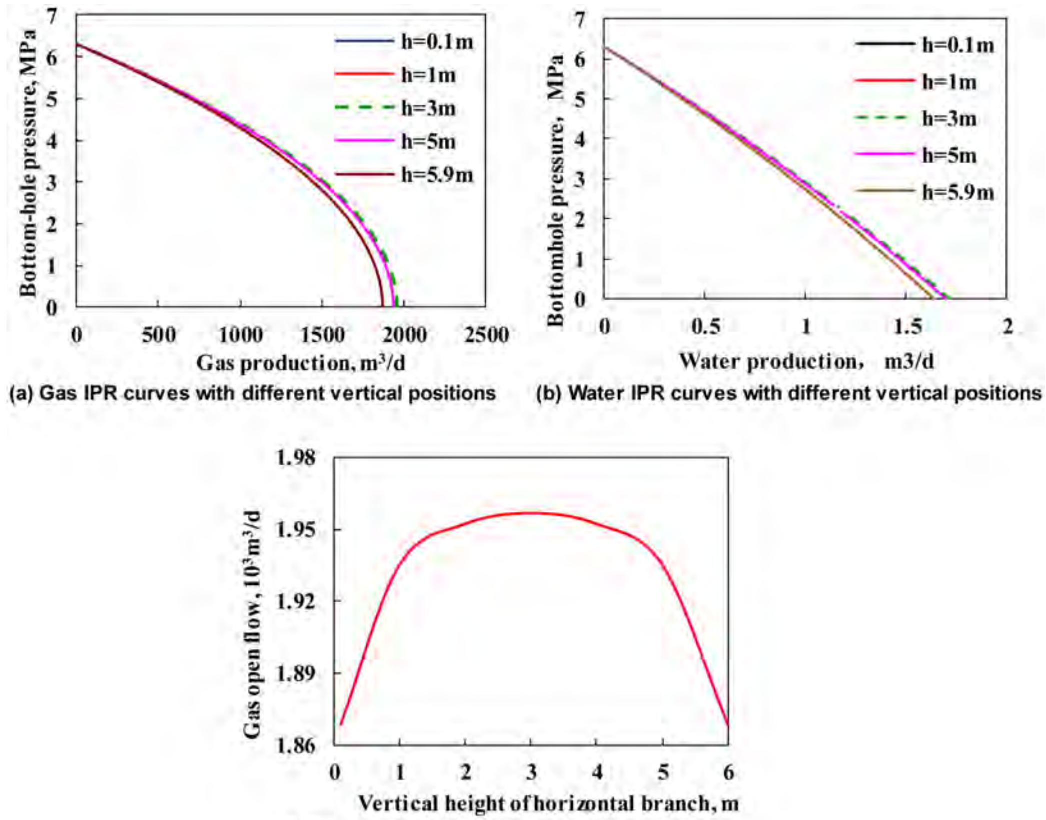
(b) Water IPR curves with different build-up section horizontal distances



(c) Gas open flow with different build-up section horizontal distances

Figure 6—Gas and water IPR curves and gas open flow with different build-up section horizontal distances

The effect of branch vertical position. Different branch vertical positions make different seepage path. In order to determine which vertical position is the best for production, several heights of horizontal branches are given to be verified. The effect of gravity is not included in these cases. It can be seen in Figure 7 (a) and (b), the water and gas productions perform best when the height of horizontal branch is 3 m, which means the branch is located in the vertical center of the formation. And as Figure 7 (c) shows, absolute open flow is symmetrical with vertical location. Closer to both upper and lower boundaries, the absolute open flow decreases faster.



(a) Gas IPR curves with different vertical positions (b) Water IPR curves with different vertical positions

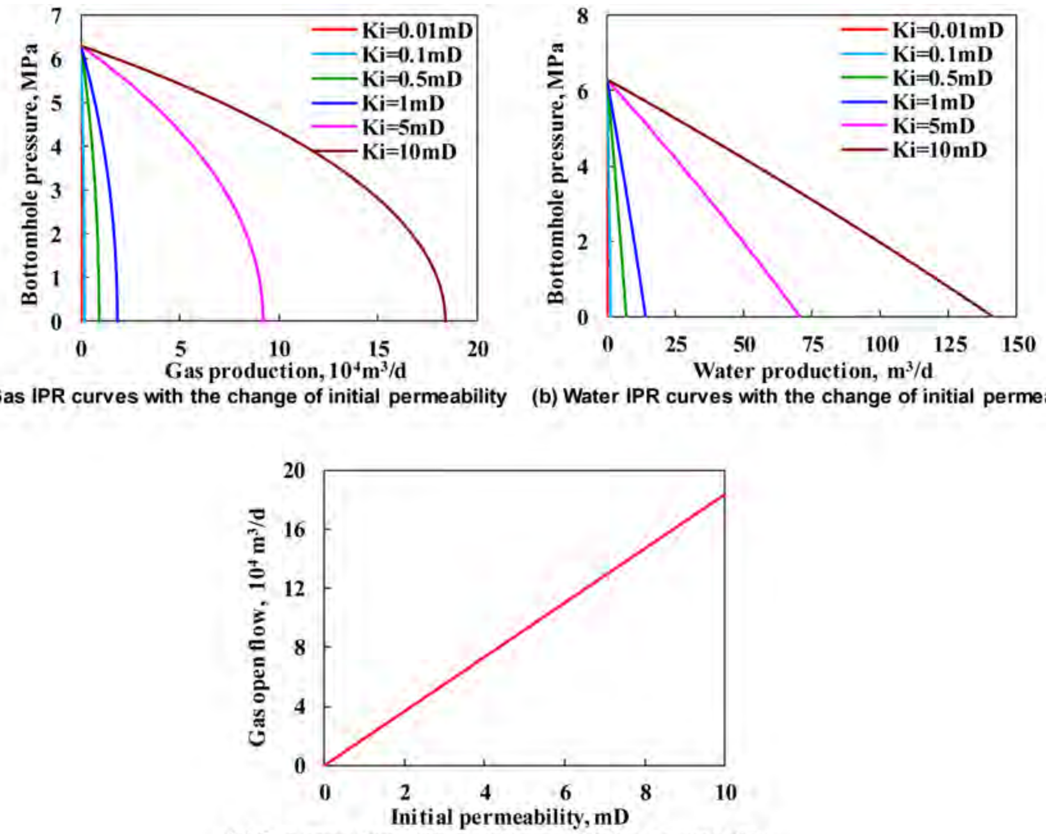
(c) Gas open flow with different vertical positions

Figure 7—Gas and water IPR curves and gas open flow with different vertical positions

The effect of the reservoir properties

During the production of unconventional gas, the reservoir permeability changes with pressure. There exisit stress sensitivity, matrix shrinkage, and slippage effect in coalbed methane reseroir. The influence of initial permeability, stress sensitivity, matrix shrinkage, and slippage effect on gas and water productivity of RMBH well are analyzed.

The effect of initial permeability. Figure 8 shows the variation of gas and water productivities with the initial permeability. It can be seen that both the gas and water productivity are greatly influence by the initial permeability, and the gas open flow increases linearly with the initial permeability.

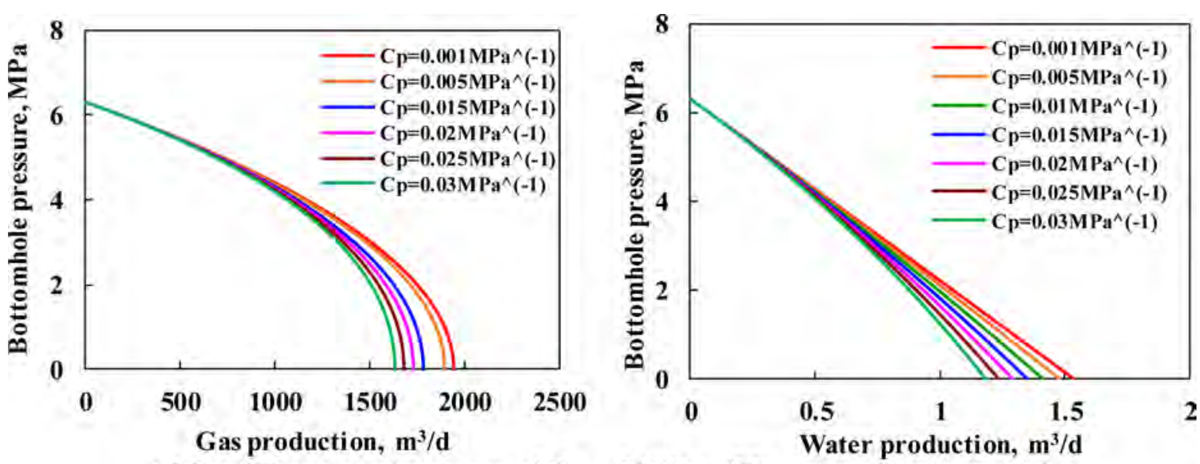


(a) Gas IPR curves with the change of initial permeability (b) Water IPR curves with the change of initial permeability

(c) Gas open flow with the change of initial permeability

Figure 8—Gas, water IPR curves and gas open flow with the change of initial permeability

The effect of stress sensitivity. Figure 9 shows the variation of gas and water productivities with different stress sensitivity effect factors. It can be seen that both the gas and water productivities decrease with the increase of stress sensitivity effect factor. Moreover, the influence of stress sensitivity is weak when the bottom-hole pressure is relatively high. When pressure drops down to a certain level, the effect of stress sensitivity becomes obvious and should not be ignored.

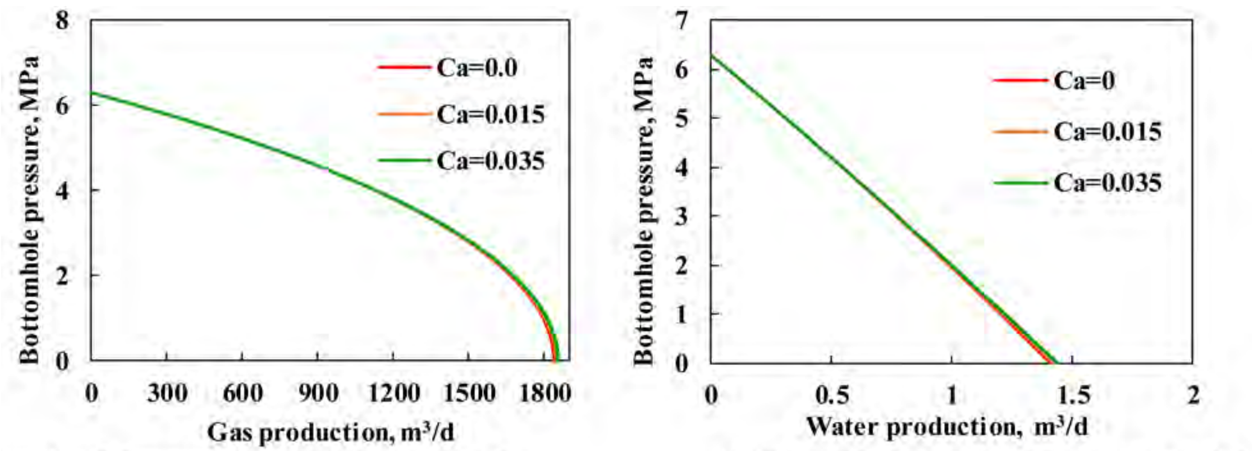


(a) Gas IPR curves with change of C_p (b) Water IPR curves with change of C_p

Figure 9—Gas and water IPR curves and gas open flow with the change of C_p

The effect of matrix shrinkage. Figure 10 shows the variation of gas and water productivities with different matrix shrinkage effect factors. The IPR curves under different matrix shrinkage effect factors

(Figure 10) almost coincide, which means the effect of matrix shrinkage parameters on productivity is not significant under the given reservoir and fluid parameters. However, it could still be seen that a larger matrix shrinkage effect factor can achieve a higher gas open flow, demonstrating that matrix shrinkage has a positive influence on production. In fact, water saturation and average reservoir pressure will change with the production of coalbed methane, matrix shrinkage may show a more obvious impact on productivity in the actual production process of coalbed methane (Shi et al., 2018).



(a) Gas IPR curves with different values of C_a (b) Water IPR curves with different values of C_a

Figure 10—Gas, water IPR curves and gas open flow with different matrix shrinkage factors

The effect of slippage effect. Slippage effect is also a positive effect for gas production, as shown in Figure 11. The gas productivity increases with b at low pressure (when $p_{wf} < 1.5$ MPa). That is to say, the slippage effect mostly affects the late stage of production.

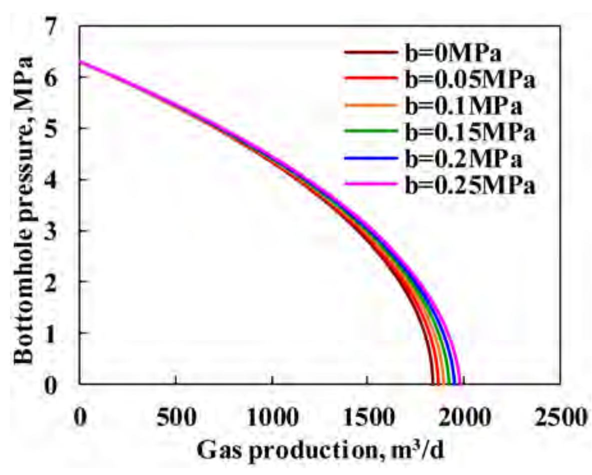


Figure 11—Gas IPR curves with different slippage coefficients

The effect of water saturation at different production stages

During the whole production process, water saturation decreases gradually. In the early stage of production, water saturation is relatively high, and the main process is water drainage and pressure reduction. In the late stage, the water yield decreases and gas production dominates. At that time, the water saturation of coal reservoir is low. Figure 12 respectively show the changes of gas and water productivity with different water saturation. For the water productivity equation, the given Sw is from 0.1 to1; for the gas productivity equation, the given Sw is from 0 to 0.9. It can be seen from Figure 12 (a) that the gas production increases with the decrease of water saturation, and the increasing extent of production slows down with decreasing water saturation. In Figure 12 (b), the water production decreases with the decrease of water saturation, and the decreasing extent of water production increases first and then decreases with decreasing water saturation.

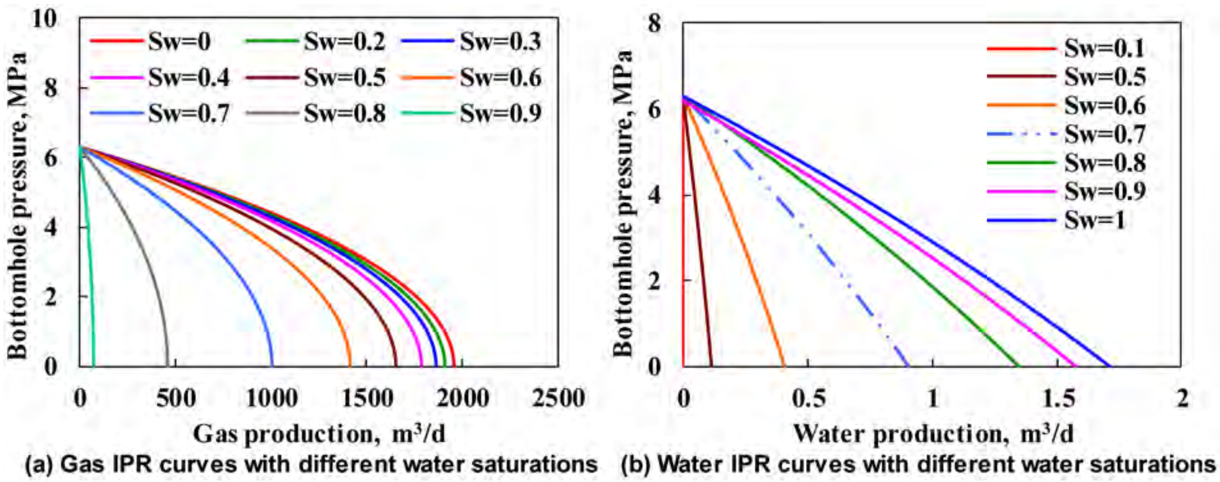


Figure 12—Gas and water IPR curves with different water saturations

Conclusions

1. Productivity equation of radial multi-branch horizontal (RMBH) well in unconventional natural gas reservoirs has been established, in which the dynamic permeability influenced by stress dependence, gas slippage, and matrix shrinkage is taken into consideration.
2. Radial horizontal well with two branches can degenerate to the conventional horizontal well when build-up section horizontal distance is zero. Preliminary calculation case indicates the resistance of the degenerated RMBH well model with two branches is very close to that of conventional horizontal well, and its external resistance is almost same as the resistance of vertically fractured well proposed by former researchers. It shows that the RMBH productivity model is reasonable and accurate.
3. In the formation with relatively large difference between maximum stress and minimum stress, the complex fracture network cannot be easily generated, and the fracture will mainly propagate in direction of maximum stress. In this case, the RMBH well shows more advantage than vertically fractured well. This type of well configuration may be an alternative technique for improving gas production in unconventional gas reservoirs.
4. The gas production rate of RMBH well is sensitive to branch length, branch number, and build-up section horizontal distance, and branch length has the greatest influence. Sensitivity analyses demonstrate that radial horizontal well with 4 branches has largest economic benefit. In addition, stress dependence effect affects the permeability most as well as gas production rate, while gas slippage and matrix shrinkage have little effect on gas production. The permeability variation owing to stress dependence effect should be incorporated into productivity equation of unconventional gas wells.

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