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Research Article

A Method to Improve Computational Efficiency of Productivity Evaluation with Rectangular Coalbed Methane Reservoir

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Computational efficiency is the key factor to be considered in the productivity evaluation of rectangular coalbed methane reservoir. There are three main factors affecting the calculation speed: the nonlinearity of the material balance equation of coalbed methane reservoir, the poor conductivity of fractures cannot be considered as infinite conductivity fractures, and the Duhamel convolution is needed in history fitting and boundary image inversion. At present, there is no method to quickly evaluate the productivity of finite conductivity fracture model in rectangular coalbed methane reservoir. Diffusion equation of matrix is generated by the Fick diffusion law. The Darcy seepage law is used to build the seepage equation of fractured system in coalbed methane reservoir. In order to transform the calculation result of infinite conductivity fracture into finite conductivity fracture, fracture conductivity factor is employed in this paper. The applicability of fracture conductivity factor in the whole production process is clarified. It is clear that the factor is prone to calculation errors when the time is small, and the calculation fluctuates greatly. According to the characteristics of the Riley method and discrete method, an accurate and efficient analytical solution calculation process is designed. This will make the calculation results accurate. A production evaluation method of rectangular coalbed methane reservoirs with fractured vertical well and finite conductivity fracture is proposed. The purpose of quickly and accurately predict well production capacity is reached. The geological parameters are recombined, and new coalbed methane reservoir flow parameters are defined. Through parameter sensitivity analysis, the influence of different flow characteristic parameters on gas production is clarified. The dimensionless transfer constant and dimensionless storage capacity affect the appearance time of desorption and diffusion and the storage capacity of the fracture system, respectively. The dimensionless desorption constant describes the strength of desorption and diffusion. The influence of fracture conductivity factor on production is studied. It is clarified that its impacts are different in the early stage and the later stage of production. There is a limit to the fracture conductivity factor. When the limit is exceeded, the fracture conductivity factors no longer affect the production of a single well. The findings of this study can understand the percolation stage of finite conductivity fractured wells with rectangular coalbed methane reservoir and can also guide fracturing design and writing in the field. The research results enrich the productivity evaluation model of coalbed methane reservoir. In the end, a set of production evaluation method is put forward suitable for the well in rectangular coalbed methane reservoirs with fractured vertical well and finite conductivity fracture. In this paper, the influence of fracture conductivity on single well productivity in rectangular coalbed methane reservoir is quantitatively evaluated for the first time. By improving the calculation method and optimizing the calculation path, the productivity evaluation calculation speed of finite conductivity fractured wells in rectangular coalbed methane reservoir is optimized without affecting the calculation accuracy. The new method can be applied directly to productivity evaluation software, which has the significance of popularization.

1. Introduction

Coalbed methane is considered as one of the dangerous sources in coal mining. There are two main occurrence modes of CBM in coal seam: adsorbed gas and free gas. Free gas exists in the same form as conventional gas reservoirs. Under the condition of original formation, adsorbed gas is mainly adsorbed in coal rock matrix [1]. With the early drainage of coalbed methane wells, the formation pressure gradually decreases. When formation pressure reaches the critical desorption pressure, the adsorbed gas will gradually separate from the coal rock matrix and become free gas. Current research shows that the porosity of coal seam is small, usually less than 1%. The production contribution of coalbed methane is mainly adsorbed gas. The separation and migration of free gas must be considered when evaluating the capacity of coalbed methane reservoir.

The Langmuir isothermal adsorption equation is used to describe the dynamic balance between free gas and adsorbed gas. Fick's diffusion law is used to describe the process of free gas entering the natural fracture system of coal seam by diffusion. Fick's first diffusion law describes quasisteady-state diffusion, and Fick's second diffusion law describes unsteady diffusion. The analytical solution model of coalbed methane productivity is based on the dual-medium model of conventional gas reservoirs proposed by Warren and Root [2] and De Swaan [3]. Anbarci and Ertekin [4] introduced the Langmuir isothermal adsorption equation based on molecular motion theory to describe the desorption process of adsorbed gas. The Fick diffusion equation of mass transfer was introduced to describe the process of desorption gas migration from coal matrix to fracture system. The introduction of these two equations greatly increases the accuracy of CBM seepage model. With the wide application of reservoir reconstruction technology in unconventional gas reservoir development, Nie et al. [5] and Yu-Long [6] analyzed the analytical solution of the model with artificial fracture and analyzed its flow stage and pressure production change. Li et al. [7] studied the seepage characteristics of coalbed methane reservoir and the productivity characteristics with the presence of stimulated reservoir volume. Fu [8] studied the influence of hydraulic fracturing of coal seam on roof rupture and instability by physical simulation experiment. Based on the production characteristics of coalbed methane wells in Hancheng field, Zhiming et al. [9] summarized three typical models of coalbed methane production. Jun et al. [10] explored the geological control factors that govern the productivity of coalbed methane wells on a small scale. By using the method of geological analysis and grey correlation analysis, the geological and drainage data of 26 coalbed methane production wells over 5 years in Zhengcun block were systematically analyzed. Based on the basic unit of the dual-pore model, Long and Rigui [11] deduced the shape factors suitable for the dual-pore model of coalbed methane reservoir by considering the Darcy flow, molecular diffusion movement, gas desorption effect, slippage effect, and other seepage mechanisms. Lijun et al. [12] put forward the concept of controllable horizontal well design, realizing the design objectives of controllable well, easy to transform, fast and efficient, and widely adaptable. Bo et al. [13] systematically described the key drilling technology successfully implemented for tree-like horizontal well, which provides a new means for the efficient development of coalbed methane. In recent years, nitrogen foam fracturing has been used in more and more CBM wells, and good results have been achieved. Nitrogen foam fracturing can increase the conductivity of fractures.

Wei [14] constructed a conceptual model of discrete fracture network using unstructured perpendicular bisection grid, established a mathematical model considering shale gas reservoir permeability, Darcy flow, diffusion, and adsorption/desorption stress sensitivity, derived and obtained nonlinear numerical equation of production decline, obtained production decline curve, and identified the flow stage of the model. Li X. et al. [15] evaluated the productivity of nitrogen foam fracturing CBM wells through production data analysis and found that nitrogen foam fracturing had significantly better effect than hydraulic fracturing. Based on logging, experimental testing, and drainage data of a research area in Qinshui Basin, Qiao et al. [16] carried out research on coalbed methane reservoir productivity prediction technology and calculated the weight of each reservoir parameter affecting coalbed methane reservoir productivity through grey correlation analysis method. A polynomial exponential model is established by using four parameters of gas content, ash content, porosity, and permeability to predict coalbed methane reservoir productivity. Li [17] introduced a special quasitime function to solve the nonlinear problem of CBM material balance equation. Using the newly defined parameters to characterize the asymmetry of hydraulic fractures, the productivity evaluation model and its analytical solution with different degrees of symmetry of fractures are obtained. The permeability of coalbed methane reservoir is low according to well test. The seepage range of coalbed methane wells for hydraulic fracturing is almost limited to the rectangular area with hydraulic fracture as the center line. At present, the hydraulic fracture in the model proposed by most scholars is a hyperpermeability channel. The fracture is assumed to have infinite conductivity, with fluid from the reservoir instantaneously flowing into the wellbore with equal flow throughout the fracture and no pressure drop. Actual hydraulic fractures do not have infinite conductivity. Especially for the soft stratum such as coal seam, the hydraulic fracture conductivity is generally small. Fracture conductivity should be considered in the evaluation of single well productivity and gas reservoir development potential. In productivity evaluation, the finite conductivity characteristics of rectangular boundary and fracture will bring a huge amount of calculation. The increase of calculation will affect the application of the model in gas reservoir development.

Previous studies mainly focused on circular boundary and rarely involved rectangular boundary. But according to the seismic data, rectangular boundary is more common in coal seam. Taking the no. 1 coalbed methane block as an example, it is found that the fracture conductivity coefficient of fractured vertical wells is generally between 1 and 10, and 38% of wells are suitable for rectangular boundary model.

Under the influence of reservoir structure, fracture conductivity coefficient of fractured vertical wells in no. 2 coalbed methane block is generally below 5, and 27% of wells are suitable for rectangular boundary model. Based on the rectangular boundary, this paper increases the applicability of the model and enriches the productivity evaluation model of coalbed methane. In addition, previous studies mainly focused on increasing the accuracy of the model while ignoring the calculation speed of the model. However, due to the complexity of coalbed methane, the calculation amount of the productivity evaluation model is increased, so the previous model is still in the theoretical stage, with few applications. In this paper, the fracture conductivity conversion factor is introduced to optimize the calculation path, avoid the error caused by the fracture conductivity conversion factor, and greatly increase the calculation speed. The model presented in this paper can be embedded into current productivity evaluation software to achieve direct application.

First, the methodology is presented. Then, the gas migration model in the matrix was determined by the Langmuir equation and Fick diffusion law. The gas flow model in the natural fracture system was determined by the flow material balance equation, and the fracture conductivity conversion factor was introduced to solve the seepage problem of finite conductivity fractures. Then, the conclusion is analyzed, including the influence of fracture conductivity on production and the sensitivity of parameters. The calculation path of capacity evaluation is optimized, and the calculation speed is increased without affecting the calculation accuracy. Finally, the model is used to fit the historical production data and forecast the future production of a coalbed methane well in Bowen Basin.

2. Methodology

In order to simplify the seepage model, important assumptions need to be made:

(1) The gas reservoir is a constant temperature

(2) The properties of each point in the gas reservoir are consistent

(3) Hydraulically fractured vertical wells are located in the middle of the gas reservoir (Figure 1).

(4) Gas is desorbed from the matrix and diffused into the natural fracture system. The Darcy flow is followed in a natural fracture system (Figure 2)

(5) Hydraulic fracture is a finite conductivity fracture

(6) Vertical well production mode is constant pressure production or constant flow rate production

(7) The coalbed methane reservoir is rectangular with a closed boundary or a constant pressure boundary

(8) Unsteady and quasisteady gas diffusion occurs in the matrix micropore system of coal seam (Figure 3)

(9) The gas reservoir does not percolate vertically

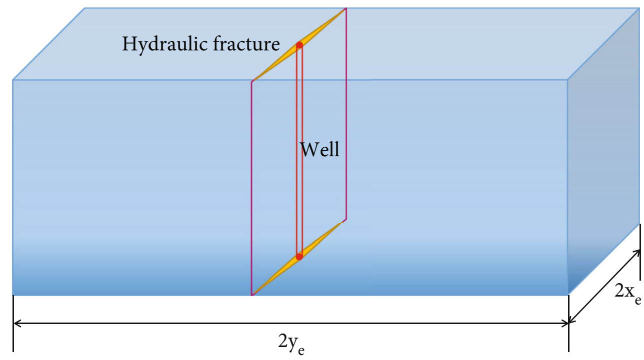


Figure 1: Hydraulically fractured wells located in the middle of the rectangular coalbed methane reservoir.

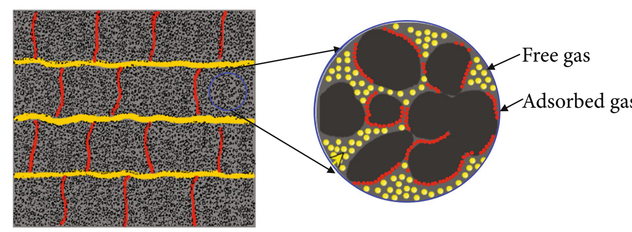


Figure 2: The adsorbed gas and free gas in coalbed methane.

2.1. Model Establishment and Solution. Anbarci and Ertekin [4] proposed a coalbed methane reservoir seepage model based on the conventional double porosity model. In this model, the fracture is an infinite conductivity fracture.In this article, fractured well with finite conductivity in rectangular-shaped coalbed methane reservoirs was discussed, using the spherical matrix to describe the transient steady state sorption and using the cubic matrix to describe the pseudosteady-state sorption.

2.2. Modeling Flow in the Nature Fracture. Free gas and desorbed gas flow together in coalbed methane reservoirs are different from conventional gas reservoirs. This makes the material balance equation become nonlinear equation. The material balance equation in the nature fracture is as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{p}{\mu z}\frac{\partial p}{\partial r}\right)=\frac{\phi c_g p}{kz}\frac{\partial p}{\partial t}+\frac{p_{sc}T}{kT_{sc}}\frac{\partial V}{\partial t}. \quad (1)$$

Equation (1) is a nonlinear equation. At present, there is no accurate analytical solution for nonlinear equation, so it needs to be solved by numerical method.

$$\begin{aligned}\frac{1}{r}\frac{\partial}{\partial r}\left(r^2 D\frac{\partial C}{\partial r}\right)&=\frac{\partial C}{\partial t},\\ \frac{\partial C}{\partial t}&=D\frac{\partial^2 C}{\partial r^2}.\end{aligned} \quad (2)$$

Associated with diffusion equation and dimensionless transformation, the solution of formula (1) in Laplace space is as follows:

$$\frac{1}{r_D}\frac{\partial}{\partial r_D}\left(r_D\frac{\partial\widetilde{\psi_D}}{\partial r_D}\right)=f(s)\widetilde{\psi_D}. \quad (3)$$

Unsteady diffusion:

$$f(s)=\omega s+\frac{(1-\omega)}{\lambda}\sigma\left(\sqrt{\lambda s}\coth\sqrt{\lambda s}-1\right). \quad (4)$$

Quasisteady-state diffusion:

$$f(s)=\omega s+\frac{(1-\omega)}{\lambda}\sigma\frac{s}{s+1/\lambda}. \quad (5)$$

2.3. Fracture Conductivity Conversion Factor. In rectangular CBM reservoir model with finite conductivity fractures, the computational speed is the key to application. In order to consider the conductivity of fracture without increasing the amount of calculation, the fracture conductivity conversion factor can be used to transform the calculation results of infinite conductivity fracture to finite conductivity fracture. The transformation formula is [18] as follows:

$$s\tilde{p}_{wD}=s\tilde{p}_{w\mathrm{Dinf}}+s\tilde{f}\left(C_{fD}\right). \quad (6)$$

$\tilde{p}_{w\mathrm{Dinf}}$ is the calculation result of infinite conductivity fracture, and $\tilde{f}(C_{fD})$ is convert conductivity factor for fracture. According to the calculation results of Riley [18], this factor can be expressed as follows:

$$s\tilde{f}\left(C_{fD}\right)=2\pi\sum_{n=1}^{\infty}\frac{1}{n^2\pi^2C_{fD}+2\sqrt{n^2\pi^2+s}}+\frac{0.4063\pi}{\pi\left(C_{fD}+0.8997\right)+1.6252s}. \quad (7)$$

3. Result and Discussion

3.1. Analysis of Fracture Conductivity. Even under the condition of the same geological characteristics, the hydraulic fracture conductivity is different. Due to the large gas flow in the early stage, fracture conductivity becomes the bottleneck of single well productivity. The influence mainly occurs in the early stage of production. With the increase of fracture conductivity, energy consumption decreases and single well productivity increases at the same flow rate. When the dimensionless conductivity factor of fracture is about 12, the conductivity of fracture almost no longer affects the productivity of single well. With proper fracturing technology, the conductivity factor of hydraulic fracture can easily reach 12. There is no need to increase the fracturing scale to pursue fracture conductivity. For most CBM reservoirs, the dimensionless fracture conductivity factor is usually less than 12, and its impact on single well productivity must be considered during productivity evaluation (Figure 4).

3.2. Parameter Sensitivity Analysis. In order to better describe the flow in the reservoir, it is necessary to recombine the geological parameters into flow characteristic parameters. Flow characteristic parameters mainly include dimensionless transfer constant λ, dimensionless storage capacity ω, and dimensionless desorption constant σ. In addition, always with the well storage coefficient and well skin factor, these five parameters are used to analyze the pressure sensitivity of coalbed methane. The basic parameters of sensitivity analysis are shown in Table 1. Parameter sensitivity analysis based on the closed gas reservoir model.

The dimensionless transfer constant λ is directly proportional to permeability and analytical time constant and inversely proportional to reservoir porosity, gas viscosity, fracture half-length, and gas compressibility. Because the desorption time is inversely proportional to the dimensionless desorption constant, dimensionless transfer constant is inversely proportional to the desorption intensity. The larger the dimensionless transfer constant is, the later the “descent” feature in the pressure curve appears, and the later the desorption and diffusion control stage appear. Therefore, dimensionless transfer mainly affects the time when desorption and diffusion occur and has a weaker effect on the degree of desorption and diffusion (Figure 5(a)).

The dimensionless storage capacity ω is directly proportional to the porosity of the fracture system and reflects the storage capacity of fracture system. Contrary to the conventional dual-porous media model reflecting the storage capacity of the matrix, the dimensionless storage capacity represents the proportion of gas flow in the reservoir from the fracture system. When the dimensionless storage capacity is high, the more gas from the fracture system is produced, and the less gas will be diffused from the matrix. In this case, the desorption and diffusion of coalbed methane reservoir are not obvious. The pressure derivative curve is different than that of conventional dual porosity reservoir, and the “downward concave” shape of pressure derivative becomes smaller. In the early stage, as the seepage occurs in natural fractures, the pressure drop decreases for gas reservoirs with large storage capacity, the linear flow time increases, and the desorption diffusion is delayed and the time becomes shorter (Figure 5(b)).

The dimensionless desorption constant σ mainly describes the strength of desorption and diffusion. It is directly proportional to Langmuir volume, production rate, and original reservoir pressure. The original reservoir pressure determines the Langmuir volume. The greater the original pressure, the gas adsorbed in the coal seam will increase. Therefore, Langmuir volume also represents the ability of gas desorption in the matrix to recharge the fracture system. The larger the Langmuir volume, the faster the gas concentration changes in the reservoir. All of these will lead to the enhancement of desorption and diffusion, which makes the “sag” phenomenon of the pressure derivative curve stronger (Figure 5(c)).

The well storage coefficient mainly affects the early stage of production. Well storage coefficient reflects the size of well storage effect. It determines both the degree and the duration of well storage effect. If the well storage effect is too large, it will cover the linear flow stage and make the production directly enter into the CBM desorption and diffusion stage (Figure 5(d)).

The skin factor mainly affects the pressure drop in the transition stage of well storage. After the wellbore storage

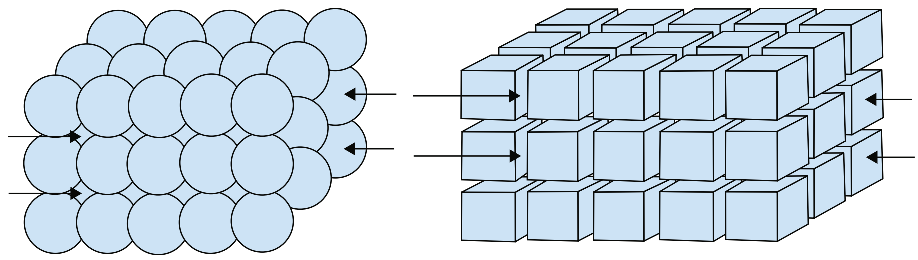


FIGURE 3: Unsteady state (a) and pseudosteady state (b) sorption/diffusion.

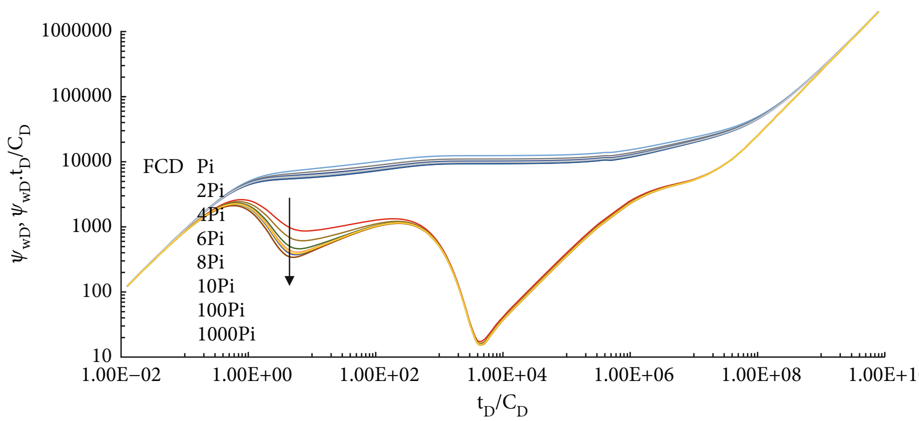


FIGURE 4: Different dimensionless bottomhole pressure with different dimensionless fracture conductivity.

TABLE 1: The basic parameters with sensitivity analysis.

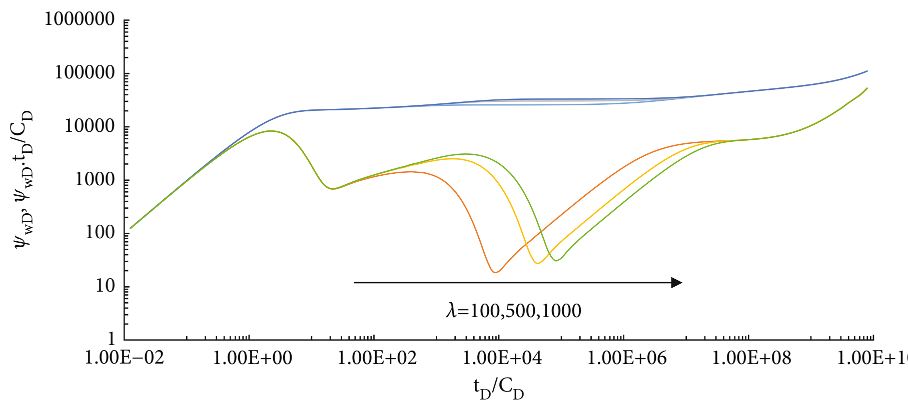
σ	ω	λ	C_D	s	x_{eD}	y_{eD}
500	0.5	500	10	5	100	50

phase, it evolves into the wellbore transition phase. The skin effect appears. Skin factor mainly affects the transition stage between well storage stage and unsteady flow stage. The skin factor represents the degree of contamination near the well. At the same flow rate, an increase in skin factor will lead to an increase in near-wellbore pressure drop (Figure 5(e)).

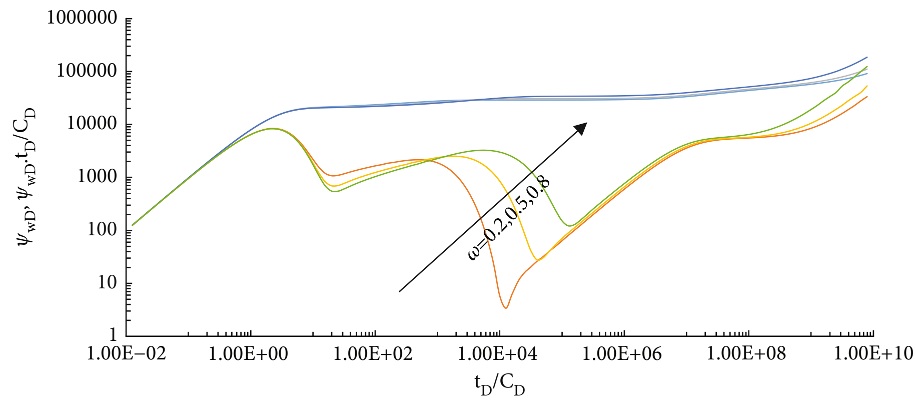
3.3. Verification of the Fracture Conductivity Conversion Factor. Figure 6 shows comparison of calculation time under different fracture conductivity conditions. The Riley method (1991) and the discrete method are for the same mathematical model. It can be seen from the figure that the Riley method has a greater computational speed advantage. The average calculation speed of the Riley method is 19 times fast as that of discrete method. This is because the Riley method does not need to discretize the cracks during the calculation process. So the Riley method does not need to solve a system of equations at every time step. This greatly saves calculation time. In addition, with the increase of fracture conductivity, the error between the Riley method and the discrete method gradually decreases. As the fracture conductivity increases from 1 to 100 (Figure 6), the errors between model A and model B are 2.8%, 1.6%, 1%, 0.6%, and 0.4%, respectively. All the errors were less than 3% (note: fitting error is defined as $|\text{value}_{\text{Riley method}} - \text{value}_{\text{discrete method}}|/\text{value}_{\text{discrete method}}$).

But there are some problems when using the Riley method. The curves of the same color in Figure 7 represent the results of calculations using different methods with the same conversion factor. The curves represent the results of calculation using accurate discrete method. The dotted curve represents the results of calculation using the Riley method. However, when the time is small, the method is prone to errors. When the dimensionless time is less than 1.0E-4, the error caused by the Riley method is larger. When the dimensionless time is more than 1.0E-4, the calculation result of the Riley method is consistent with discrete method. Moreover, when the dimensionless conductivity of the fracture is greater than 100, the results of Riley method and discrete method are consistent. If the fracture conductivity factor is greater than 100, the calculated results of the two methods are consistent. At this time, considering the calculation speed, the Riley method is preferred.

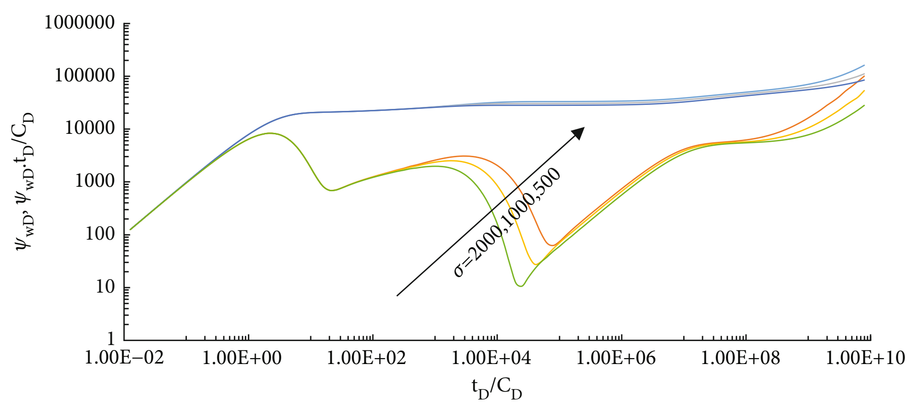
In practice, the Riley method can be combined with discrete method. When the dimensionless time is less than 1.0E-4, more accurate but time-consuming discrete method can be used. In this case, the time is relatively small and does not affect the overall computing speed. If the dimensionless time is greater than 1.0E-4, the Riley method can be used. According to the study in this paper, the accuracy of the Riley method is guaranteed at this time (Figure 8). In this way, the combination of the two methods ensures the accuracy and efficiency of calculation. In addition, the variables in the calculation are dimensionless, so the calculation process is not limited by the geological characteristics of the gas reservoir itself. Before there is dimensional change, it is a purely mathematical problem.



(a)

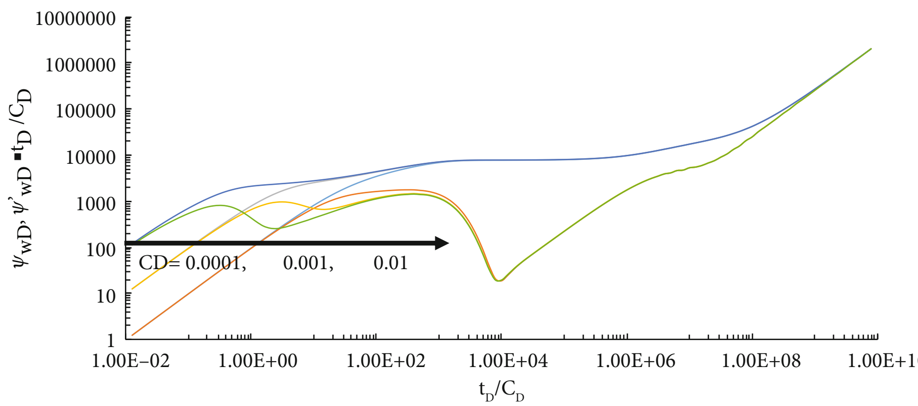


(b)

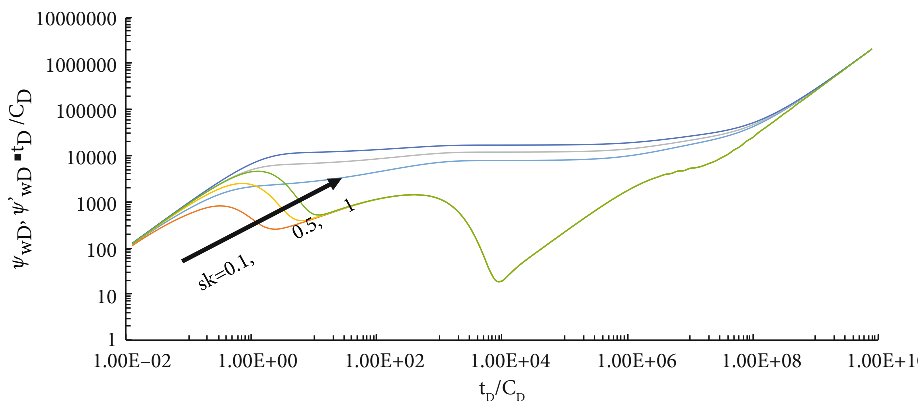


(c)

Figure 5: Continued.



(d)



(e)

Figure 5: (a) Influence of cross-flow coefficient on the pseudopressure and pseudopressure derivative. (b) Influence of storage ratio on the pseudopressure and pseudopressure derivative. (c) Influence of desorption constant on the pseudopressure and pseudopressure derivative. (d) Influence of well storage coefficient on the pseudopressure and pseudopressure derivative. (e) Influence of skin coefficient on the pseudopressure and pseudopressure derivative.

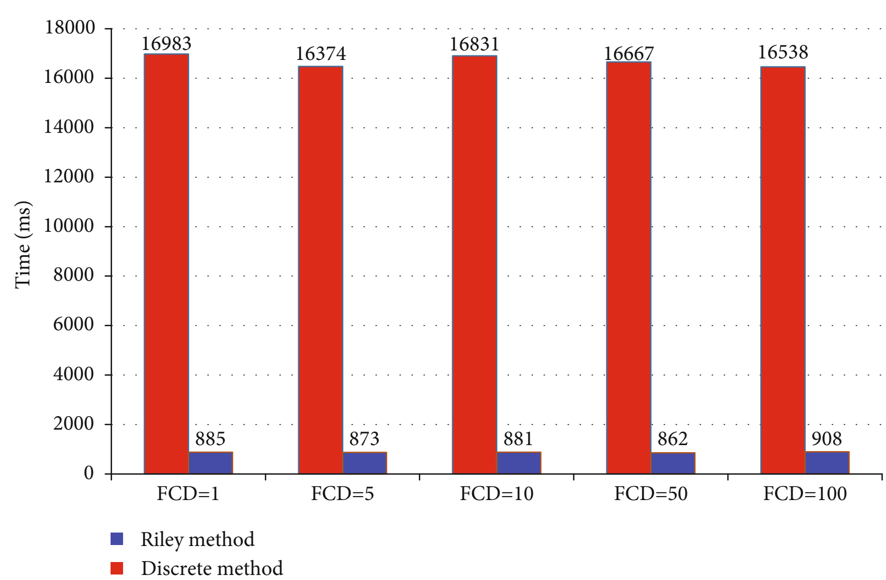


Figure 6: Comparison of calculation time between the Riley method and discrete method.

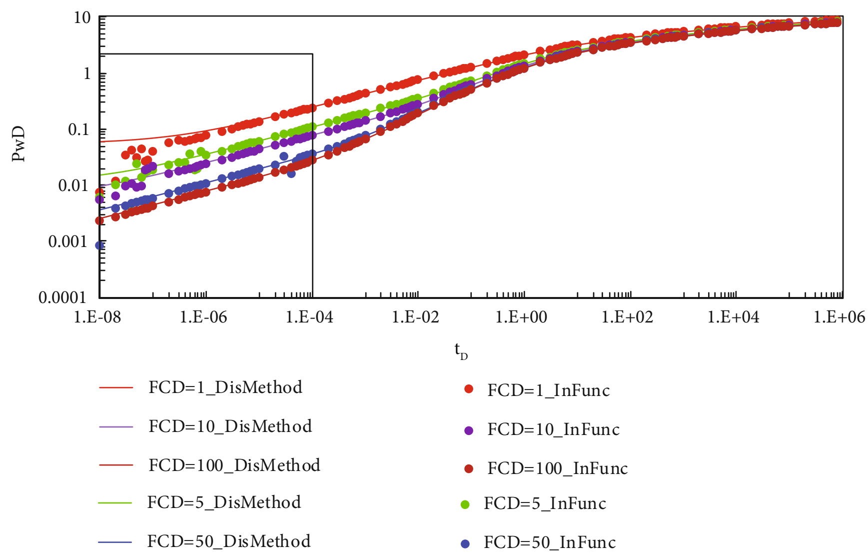


Figure 7: The Riley method causes errors when the time is small.

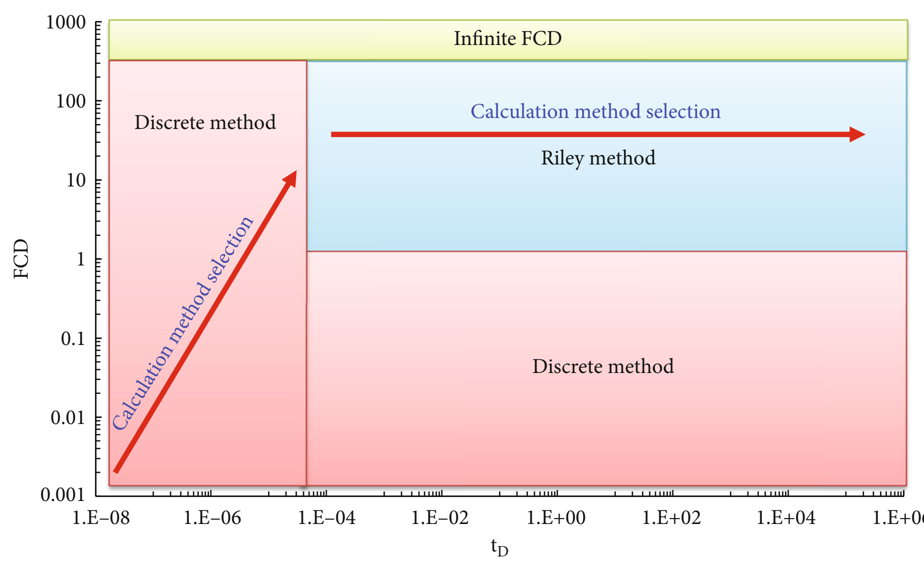


Figure 8: The calculation method selection between the Riley method and discrete method.

Table 2: Example of single well basic data.

p_{ic} (MPa)	s	k (md)	ρ_g (g·m^{-3})	x_e (m)	y_e (m)	h (m)
2.08	0	3.37	1.47	800	800	10
R_w (m)	T (k)	φ	V_L (cm^3·g^{-1})	L_f (m)	P_L (MPa)	C_f (kp^{-1})
0.3	287.15	0.2	9.97	160	1.15	2.9e^{-6}

4. Field Application

The example well is a CBM fracturing vertical well in Bowen Basin, Western Australia. The basic data of the well are shown in Table 2. According to the seismic data, there are sealing faults around the well. It can be approximated as a rectangular gas reservoir. The model in this paper is used for productivity evaluation. The Duhamel convolution is used to fit the well production, accumulated production, and bottomhole flow pressure with the productivity equation. Under the optimal fitting parameters, the fitting error of production is 8.9% (Figure 9), the fitting error of cumulative production is 1.8% (Figure 9), and the fitting error of pressure is 17.7% (Figure 10). The evaluation results are in line with the basic understanding of gas reservoir, and the error is small. Based on the historical matching, the future

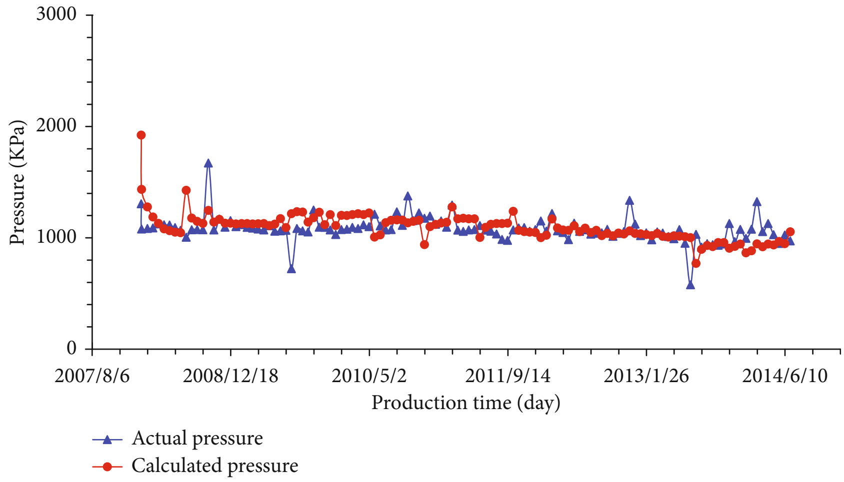


Figure 9: Fitting of production and cumulative production in a single well.

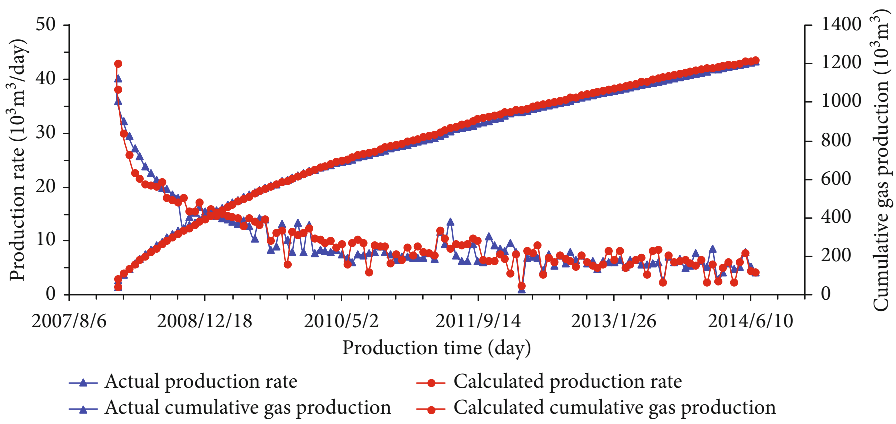


Figure 10: Single well pressure fitting.

production of the well can be predicted and the productivity of the well can be evaluated (note: fitting error is defined as $|\text{value}_{\text{actual}} - \text{value}_{\text{calculated}}|/\text{value}_{\text{actual}}$).

5. Summary and Conclusions

(1) The main parameters affecting the pressure curve of CBM can be recombined as dimensionless transfer constant, dimensionless storage capacity, dimensionless desorption constant, well storage coefficient, and skin factor. The dimensionless transfer constant mainly affects the time when desorption and diffusion occur and has a weaker effect on the degree of desorption and diffusion. The dimensionless storage capacity reflects the storage capacity of the fracture system, and the dimensionless desorption constant describes the strength of desorption and diffusion. Well storage coefficient and skin coefficient affect the initial stage of production

(2) The bottleneck effect of fracture conductivity mainly occurs in the early stage of production. Single well productivity increases with fracture conductivity. When the dimensionless conductivity factor of fracture is over 12, the conductivity of fracture almost no longer affects the productivity of single well

(3) By optimizing the calculation method, the productivity evaluation and calculation speed of finite conductivity fractured wells in rectangular coalbed methane reservoir can be significantly improved. The calculation results show that the calculation speed can be improved 18 to 19 times, while the calculation error can be controlled within 3%.

(4) For vertical wells with low conductivity fractures, the productivity evaluation model of fractured vertical wells with limited conductivity fractures can matched better with the field production data. Under the optimal fitting parameters, the fitting errors of production, cumulative production, and pressure are 8.9%, 1.8%, and 17.7%, respectively. The evaluation results are more accurate and reliable

Abbreviations

r: Radius of coalbed methane reservoir, m

p: Gas reservoir pressure, MPa
μ: Gas viscosity in the gas reservoir, mpa·s
Z: Gas deviation factor, dimensionless
ϕ: Reservoir porosity, dimensionless
c_g: Coal compressibility, MPa^{-1}
k: Reservoir permeability, D
t: Time variable, h
p_{sc}: Pressure under standard conditions, MPa
T: Gas reservoir temperature, K
T_{sc}: Temperature under standard conditions, K
V: Average matrix gas concentration, m^3/m^3
C: Volumetric gas concentration in the microspores, m^3/m^3
D: Diffusion coefficient, m^3/s
r_D: Dimensionless radius
ψ: Pseudopressure, MPa^2/cp
ψ_D: Dimensionless pseudo-pressure, dimensionless
ψ_i: Pseudopressure under initial conditions, MPa^2/cp
t_D: Dimensionless time variable, dimensionless
L_f: Half-length of hydraulic fracture, m
L_D: Dimensionless length, dimensionless
$\tilde{\psi}_D$: Dimensionless pseudo-pressure into Laplace place, dimensionless
s: Laplace variable, dimensionless
x_{eD}: Dimensionless reservoir length of the x coordinates, dimensionless
y_{eD}: Dimensionless reservoir length of the x coordinates, dimensionless
L: Reference length, in this paper L equal to half of the fracture length, m
p_L: Langmuir pressure, MPa
C_D: Dimensionless wellbore storage coefficient
C_{fD}: Dimensionless fracture conductivity
$\tilde{p}_{wD}$: Dimensionless bottomhole pressure with finite conductivity fracture
$s\tilde{p}_{w\mathrm{Dinf}}$: Dimensionless bottomhole pressure with infinite conductivity fracture.

Intermediate Variable

σ: $p_L V_L p_i^2 q_D/(p_L+p)(p_L+p_i)(p_i+p)$
Λ: $\varphi\mu c_g + (p_{sc}T\mu z/T_{sc}q_D p_i{}^2)$
ω: $\varphi\mu c_g/\Lambda$
λ: $k\tau/\Lambda L_f{}^2$
γ: $\sqrt{f(s)}$
ψ: $2\int_0^p (p/\mu z)dp$

Dimensionless

ψ_D: $(\pi khT_{sc}/p_{sc}q_{sc}T)(\psi_i-\psi)$
t_D: $kt/\Lambda L_f^2$
L_D: L/L_f

Data Availability

The data are all original; if you need any data in the article, please send me an email (email address: lichen1125@foxmail.com).

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, or publication of this article.

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