Energy Proceedings
Vol 38, 2024
ISSN 2004-2965

Fracture Parameter Inversion Method of Deep Coalbed Methane Wells After Hydraulic Fracturing Based on Production Dynamic Analysis

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ABSTRACT

Parametric inversion is recognized to be an effective method for evaluation of hydraulic fracturing performance. Based on the unsteady seepage theory, the fracture parameters inversion method of deep coalbed methane (CBM) reservoir is established and solved semi-analytically considering the gas-water two-phase flow and the multiple nonlinear seepage mechanism of gas and water in the matrix and fractures. The numerical results from the proposed method are consistent with that from the existing numerical method and the computational speed is heightened greatly. The results show that the proposed method can accurately obtain half-length of fracture, permeability of fracture and stimulated reservoir volume (SRV) using the production data entering the boundary control flow stage.

Keywords: fracture parameter inversion, deep coalbed methane reservoir, gas-water two-phase flow, curve fitting, non-linear fitting method

NONMENCLATURE

Abbreviations	
BHP	Bottom Hole Pressure
CBM	Coalbed Methane
DTS	Distributed Temperature Sensor
PDA	Production Data Analysis
SRV	Stimulated Reservoir Volume
Symbols	
B	Fluid volume factor, m^3/m^3
C_m	Compressibility of matrix, MPa^{-1}
C_F	Compressibility of fracture, MPa^{-1}
C_d	Desorption compressibility, MPa^{-1}
C_g	Gas compressibility, MPa^{-1}
C_w	Water compressibility, MPa^{-1}
C_t	Total compressibility, MPa^{-1}
E	Constrain the axial modulus, MPa
f	Proportionality coefficient
G_p	Cumulative production, m^3
H	Formation thickness, m
k	Permeability, $10^{-3}\mu m^2$
$k_{r,g}$	The relative permeability of gas
$k_{r,w}$	The relative permeability of water
K	Matrix volume modulus
n	Index
N_{qg}	Normalized gas production, $m^3/d/(MPa^2/(mPa\cdot s))$
N_{qw}	Normalized gas production, $m^3/d\cdot MPa^{-1}$
p	Pressure, MPa
p_L	Langmuir volume, m^3/m^3
q	Production rate, m^3/d
s	Laplace constant
S_w	Water saturation
t	Time, day
t_a	Pseudo-time, day
T	Temperature, K
V_L	Langmuir volume, m^3/m^3
V_p	Pore volume, m^3
W_p	Cumulative water production, m^3
x	X-direction
x_F	Half-length of fracture
y	y-direction
y_e	Half-length of fracture space, m
Z	Compressibility factor of gas
Greeks symbols	
∂	Differential operator
α	Stress sensitivity coefficient of Permeability, MPa^{-1}

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

β	Stress sensitivity coefficient of Porosity, MPa^{-1}
ψ	Pseudo-pressure, $MPa^2/(mPa \cdot s)$
φ	Porosity, m^3/m^3
φ_{ms}	Porosity influenced by matrix shrinkage, m^3/m^3
ε_l	Langmuir adsorption expansion coefficient
γ	Particle compression coefficient, MPa^{-1}
η	Coefficient of pressure conductivity, m^2/d
μ	Fluid viscosity, $mPa \cdot s$
ω_F	Width of fracture
Subscripts	
m	Parameters of matrix
F	Parameters of fracture
wf	Parameters of wellbore
g	Parameters of gas
w	Parameters of water
i	Parameters at the initial condition of the reservoir
r	Reference values
D	Dimensionless
sc	Surface condition

1. INTRODUCTION

The coal gas industry has entered a rapid development period in China since "Eleventh Five-Year" plan. Now our country has realized the breakthrough from shallow to deep CBM reservoir. Our country is rich in deep CBM resources [1], and it is of great significance to increase the deep CBM probing development dynamics for adjusting energy structure and the achieving strategic objective of carbon peaking and carbon neutrality. Multi-stage fractured horizontal well is the key technology to acquire the economic level of deep CBM reservoir [2], and fracture parameter inversion is the key to evaluate hydraulic fracturing performance and adjust measures.

At present, scholars use many methods to obtain fracture parameters, which can be divided into two categories. One is to obtain fracture parameters through field monitoring technology, some of the most usual ones being microseismic monitoring technology. It can directly and quantitatively characterize the orientation, height, length and width of the fracture [3][4], but these parameters obtained by this method are the propagation range of the fracture, without considering whether the fracture has seepage capacity, and the actual effective fracture length is less than half of the microseismic interpretation. And the other is to establish seepage model in different stages to invert fracture parameters. Wang et al. [5][6] studied the flow patterns of primary fractures, secondary fractures and matrix based on the soaking pressure of fractured horizontal wells, and established a corresponding seepage model to invert key fracture parameters. Kurtoglu et al. [7] and Clarkson et al. [8] established semi-analytical flowback models considering the two-phase flow in the matrix and fracture, and inverted the fracture and matrix parameters by fitting the fracturing fluid flowback data. Many scholars have established a variety of well test models to study the transient behavior of horizontal wells and to invert fracture parameters such as conductivity and length. Many scholars have also established a variety of well test models to study the transient behavior of horizontal wells and to invert fracture parameters such as conductivity and length. Brown et al. [9] divided the reservoir into original reservoir, SRV and hydraulic fracture, and proposed a classic trilinear flow well-test model. Xiao et al. [10] further considered the multiwell pressure interference and established a method based on superposition theory, Gauss elimination and Stehsest numerical inversion method. Chen [11] further considered the complex fracture network formed after hydraulic fracturing and the two-phase seepage caused by formation water and fracturing fluid. A two-phase flow numerical well testing model with complex fractures and multi-well interference was established. In addition to the well test model, some scholars [12][13] established production data analysis (PDA) methods to invert matrix and fracture parameters. Xu [14] established a gas-water two-phase pseudo-pressure and pseudo-time analytical model for shale gas reservoirs, and used the PDA method to invert the half-length of fracture, reducing the error by 22% compared with the single-phase gas model. The above models have many similarities. All of them are based on the classical seepage theory, and the parameters are interpreted by fitting the theoretical curve and production data, but the precision of the data used is different. However, unconventional gas reservoirs are so tight that they require a long shut-in test time, and they also show a long linear flow characteristic in the production, which makes it difficult to show the typical radial flow characteristic in the well test curve, resulting in a large error in well test interpretation. The remaining models use daily production and pressure data at different stages, and the

PDA method is the least costly and the largest amount of data among them.

The existing PDA methods of unconventional reservoirs focus on single-phase flow, and there is no systematic parameter inversion method considering the complex seepage mechanisms of deep CBM reservoirs and gas-water two-phase flow. Based on the unsteady seepage theory, a seepage model for deep CBM reservoirs was established by considering the gas-water two-phase flow in the matrix and fractures and multiple seepage mechanisms, such as the change of physical property parameters with pressure, adsorption and desorption, the effect of coal matrix shrinkage and stress sensitivity on permeability. The Laplace transform, Stehfest numerical inversion and mass balance equation were used for the semi-analytical solution. Material balance time and normalized production were introduced to process the production data of variable production and bottom hole pressure (BHP). Through the nonlinear fitting of theoretical seepage model and actual production data, the fracture parameter inversion method of deep CBM reservoir based on PDA was established, which is of great significance for accurate inversion of fracture parameters and evaluation of horizontal well fracturing performance.

2. METHOLOGY

2.1 Physical model

To simulate the deep CBM reservoir with a multi-stage fractured horizontal well, the typical two-region linear flow model with gas-water two-phase flow in both fracture and matrix is established, as shown in Figure 1. There are many micro-fractures in the matrix of deep CBM reservoir. In the initial stage of production, the fracturing fluid starts to flow back, and the water produced mainly comes from the fracturing fluid in hydraulic fractures, and a small part comes from the fracturing fluid invading the matrix through micro-fractures during the hydraulic fracturing. With the fracturing fluid flow back, the free gas begins to produce, and there is gas-water two-phase flow in the matrix and fractures. Most of the free gas has been produced and the adsorbed gas has been desorbed with production time pasting. The gas and water produced in this period mainly come from the fluid channeling in the matrix to the fractures.

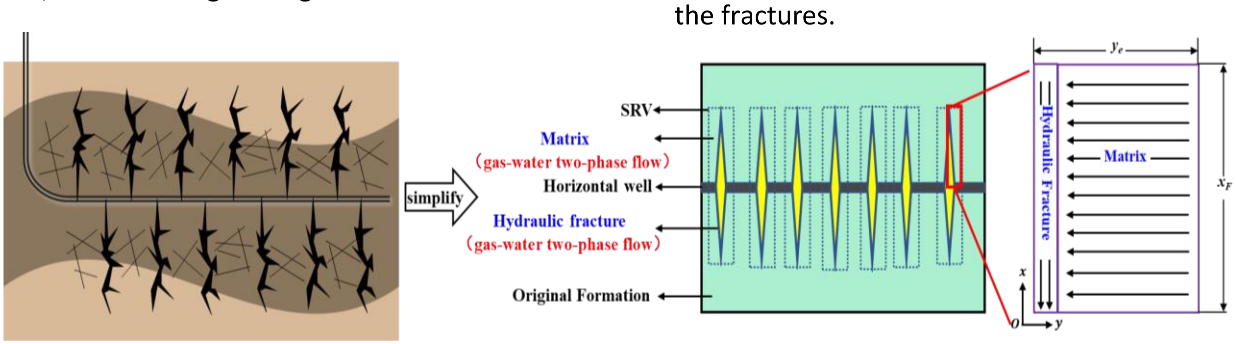

Fig. 1 Schematic diagrams of gas-water two-phase flow in deep CBM

2.2 Mathematical model

In this study, SRV is divided into two regions, matrix and fracture, which are homogeneous in the same region, and the seepage mechanism and parameters (such as porosity, permeability, relative permeability curve, compressibility, saturation and so on) are different in different regions. The flow in each region is linear, with the fracturing fluid and a small amount of gas in the fracture flowing linearly into the wellbore, and the gas and water in the matrix flowing linearly into the fracture due to the pressure difference. Then the two regions are coupled by boundary conditions, pressure and production conditions, and the seepage model of fractured horizontal wells is established to obtain the production dynamics of fractured horizontal wells.

Other assumptions of the seepage model are as follows.

(1) The production zone is horizontal, and the fractures are distributed symmetrically throughout the production zone with equal length and spacing.

(2) The original reservoir outside SRV is not considered in this paper because of its low permeability and low contribution to productivity.

(3) The matrix and fracture are both gas-water two-phase seepage, there are free gas, adsorbed gas and water in the matrix, and free gas and water in the fracture.

(4) Multiple nonlinear seepage mechanisms in matrix and fracture are considered: matrix shrinkage, adsorption gas desorption, gas parameter variation with pressure, stress sensitivity.

(5) The flow is isothermal, and the effects of gravity and capillary force on the flow are ignored.

2.2.1 Seepage model in matrix system

Considering the seepage and desorption in the matrix, the gas phase and water phase seepage equations can be characterized as follows:

$$\frac{\partial}{\partial y}\left(\frac{p_m}{Z}\cdot\frac{k_{mg}k_{mr,g}}{\mu_g}\frac{\partial p_m}{\partial y}\right)=\frac{\phi_{mg}p_m C_{tm}}{Z}\frac{\partial p_m}{\partial t} \tag{1}$$

$$\frac{\partial}{\partial y}\left(\frac{k_{mw}k_{mr,w}}{\mu_w}\frac{\partial p_m}{\partial y}\right)=\phi_{mw}C_{tm}\frac{\partial p_m}{\partial t} \tag{2}$$

Where, C_d is the desorption compressibility [15].

$$C_d=\frac{p_{sc}ZT}{p_m Z_{sc}T_{sc}}\frac{V_L p_L}{\phi_m(p_L+p_m)^2} \tag{3}$$

C_{tm} is total compressibility of the matrix.

$$C_{tm}=C_m+C_d+S_{mw}C_w+(1-S_{mw})C_g \tag{4}$$

The P-M model [16] is used to describe the changes of porosity and permeability caused by matrix shrinkage.

$$\begin{aligned}\phi_{ms}=&\phi_{m0}+\frac{1}{E}-\left(\frac{K}{E}+f-1\right)\cdot\gamma\left(p_m-p_i\right)\\&+\varepsilon_l\left(\frac{\beta p_m}{1+\beta p_m}-\frac{\beta p_i}{1+\beta p_i}\right)\frac{1}{\left(\frac{K}{E}-1\right)}\end{aligned} \tag{5}$$

$$\frac{k_{ms}}{k_{mi}}=\left(\frac{\phi_{ms}}{\phi_{mi}}\right)^n \tag{6}$$

The classical exponential model is used to describe the variation of permeability and porosity with pressure.

$$k_{mg}=k_{ms}e^{-\alpha_{mg}(p_i-p_m)}\quad k_{mw}=k_{ms}e^{-\alpha_{mw}(p_i-p_m)} \tag{7}$$

$$\phi_{mg}=\phi_{ms}e^{-\beta_{mg}(p_i-p_m)}\quad \phi_{mw}=\phi_{ms}e^{-\beta_{mw}(p_i-p_m)} \tag{8}$$

The parameters such as gas viscosity and compression factor are functions of pressure, and pseudo-time and pseudo-pressure [17] are introduced to deal with nonlinearity.

$$\psi_m(p_m)=2\int_0^{p_m}\frac{p_m}{\mu_g(p_m)Z(p_m)}dp_m \tag{9}$$

$$t_a=\int_0^t\frac{\mu_{gi}C_{tmi}}{\mu_g(\bar{p}_m)C_{tm}(\bar{p}_m)}dt \tag{10}$$

By introducing dimensionless variables (Table 1) and considering the initial condition and two boundary conditions, (1) outer boundary no flow in matrix, (2) pressure continuity between matrix and fracture, the dimensionless gas phase and water phase seepage differential equations can be written as follows:

$$\begin{cases}\dfrac{\partial^2\psi_{mD}}{\partial y_D^2}=\dfrac{1}{\eta_{mgD}k_{mr,g}}\dfrac{\partial\psi_{mD}}{\partial t_{aD}}\\ \psi_{mD}(y_D,t_{aD})\big|_{t_{aD}=0}=0\\ \dfrac{\partial\psi_{mD}(y_D,t_{aD})}{\partial y_D}\Big|_{y_D=y_{eD}}=0\\ \psi_{mD}(y_D,t_{aD})\big|_{y_D=\frac{w_{FD}}{2}}=\psi_{FD}\end{cases} \tag{11}$$

$$\begin{cases}\dfrac{\partial^2 p_{mD}}{\partial y_D^2}=\dfrac{1}{\eta_{mwD}k_{mr,w}}\dfrac{\partial p_{mD}}{\partial t_D}\\ p_{mD}(y_D,t_D)\big|_{t_D=0}=0\\ \dfrac{\partial p_{mD}}{\partial y_D}(y_D,t_D)\Big|_{y_D=y_{eD}}=0\\ p_{mD}(y_D,t_D)\big|_{y_D=\frac{w_{FD}}{2}}=p_{FD}\end{cases} \tag{12}$$

2.2.2 Seepage model in fracture system

There is only free gas in the fracture. Considering the flow of gas and water in the matrix into the fracture, the seepage equations of gas phase and water phase in the fracture can be written as follows:

$$\frac{\partial}{\partial x}\left(\frac{p_F}{Z}\frac{k_{Fg}k_{Fr,g}}{\mu_g}\frac{\partial p_F}{\partial x}\right)=\frac{\phi_{Fg}p_F C_{tFg}}{Z}\frac{\partial p_F}{\partial t}-\frac{p_F}{Z}\frac{2k_{mg}k_{mr,g}}{\omega_F\mu_g}\frac{\partial p_m}{\partial y}\Big|_{y=\frac{\omega_F}{2}} \tag{13}$$

$$\frac{\partial}{\partial x}\left(\frac{k_{Fw}k_{Fr,w}}{\mu_w}\frac{\partial p_F}{\partial x}\right)=\phi_{Fw}C_{tF}\frac{\partial p_F}{\partial t}-\frac{2k_{mw}k_{mr,w}}{\omega_F\mu_w}\frac{\partial p_m}{\partial y}\Big|_{y=\frac{\omega_F}{2}} \tag{14}$$

The exponential model is used to describe the variation of permeability and porosity caused by stress sensitivity.

$$k_{Fg}=k_{Fo}e^{-\alpha_{Fg}(p_i-p_F)}\quad k_{Fw}=k_{Fo}e^{-\alpha_{Fw}(p_i-p_F)} \tag{15}$$

$$\phi_{Fg}=\phi_{Fo}e^{-\beta_{Fg}(p_i-p_F)}\quad \phi_{Fw}=\phi_{Fo}e^{-\beta_{Fw}(p_i-p_F)} \tag{16}$$

By introducing pseudo-time and pseudo-pressure to deal with nonlinearity and considering the initial conditions and two boundary conditions, (1) outer boundary no flow in fracture, (2) the fractured horizontal well is under the constant bottom-hole pressure condition, the dimensionless differential equations for gas and water seepage can be written as follows:

$$\begin{cases}\dfrac{\partial^2\psi_{FD}}{\partial x_D^2}=\dfrac{1}{\eta_{FgD}k_{Fr,g}}\dfrac{\partial\psi_{FD}}{\partial t_{aD}}-\dfrac{2k_{mr,g}}{k_{Fr,g}C_{FgD}}\dfrac{\partial\psi_{mD}}{\partial y_D}\Big|_{y_D=\frac{w_{FD}}{2}}\\ \psi_{FD}(x_D,t_{aD})\big|_{t_{aD}=0}=0\\ \dfrac{\partial\psi_{FD}}{\partial x_D}(x_D,t_{aD})\Big|_{x_D=x_{IFD}}=0\\ \psi_{FD}(x_D,t_{aD})\big|_{x_D=0}=1\end{cases} \tag{17}$$

$$\begin{cases} \frac{\partial^2 p_{FD}}{\partial x_D^2} = \frac{1}{\eta_{FwD} k_{Fr,w}} \frac{\partial p_{FD}}{\partial t_D} - \frac{2k_{mr,w}}{k_{Fr,w} C_{FwD}} \frac{\partial p_{mD}}{\partial y_D}\Big|_{y_D = \frac{w_{FD}}{2}} \\ p_{FD}(x_D, t_D)\big|_{t_D=0} = 0 \\ \frac{\partial p_{FD}}{\partial x_D}(x_D, t_D)\Big|_{x_D = x_{FD}} = 0 \\ p_{FD}(x_D, t_D)\big|_{x_D=0} = 1 \end{cases} \tag{18}$$

2.2.3 Coupled solution for whole system

Coupled with the gas seepage model in matrix and fracture in formulas (11) and (17), the gas production in Laplace domain can be obtained as follows:

$$\bar{q}_{gD} = \frac{k_{Fr,g} k_{FgD} w_{FD} \sqrt{\alpha_F}}{\pi} \frac{1}{s} \tanh\left(\sqrt{\alpha_F} \cdot x_{FD}\right) \tag{19}$$

Where,

$$\alpha_F = \frac{s}{\eta_{FgD} k_{Fr,g}} - \frac{2k_{mr,g}\sqrt{\alpha_m}}{k_{Fr,g} C_{FgD}} \tanh\left(\sqrt{\alpha_m}\left(\frac{w_{FD}}{2} - y_{eD}\right)\right) \tag{20}$$

$$\alpha_m = \frac{s}{\eta_{mgD} k_{mr,g}} \tag{21}$$

Coupled with the water seepage model in matrix and fracture in formulas (12) and (18), the water production in Laplace domain can be obtained as follows:

$$\bar{q}_{wD} = \frac{k_{Fr,w} k_{FwD} w_{FD} \sqrt{\beta_F}}{\pi} \frac{1}{s} \tanh\left(\sqrt{\beta_F} \cdot x_{FD}\right) \tag{22}$$

Where,

$$\beta_m = \frac{s}{\eta_{mwD} k_{mr,w}} \tag{23}$$

$$\beta_F = \frac{s}{\eta_{FwD} k_{Fr,w}} - \frac{2k_{mr,w}}{k_{Fr,w} C_{FwD}} \sqrt{\beta_m} \cdot \tanh\left(\sqrt{\beta_m} \cdot \frac{w_{FD}}{2} - \sqrt{\beta_m} \cdot y_{eD}\right) \tag{24}$$

The production in equations (19) and (22) is in Laplace domain. The Stehfest method [18] is used to obtain gas and water production in real domain.

Tab. 1 Definitions of the dimensionless parameters

Dimension variables	Definition	Dimension variables	Definition
dimensionless gas production rate	$\frac{1}{q_{gD}} = \frac{k_r H\left(\psi_i - \psi_{wf}\right)}{1.291\times10^{-3} q_g T}$	dimensionless water production rate	$q_{wD} = \frac{1.842 q_w B_w \mu_w}{k_r H\left(p_i - p_{wf}\right)}$
dimensionless pseudo-pressure	$\psi_D = \frac{\psi_i - \psi}{\psi_i - \psi_{wf}}$	dimensionless pressure	$p_D = \frac{p_i - p}{p_i - p_{wf}}$
dimensionless pseudo-time	$t_{aD} = \frac{\eta_r}{L_r^2} t_a$	dimensionless time	$t_D = \frac{\eta_r}{L_r^2} t$
dimensionless distance in the x direction	$x_D = \frac{x}{L_r}$	dimensionless distance in the y direction	$y_D = \frac{y}{L_r}$
dimensionless half-length of fracture	$x_{FD} = \frac{x_F}{L_r}$	dimensionless width of fracture	$\omega_{FD} = \frac{\omega_F}{L_r}$
dimensionless gas permeability in the matrix	$k_{mgD} = \frac{k_{mg}}{k_r}$	dimensionless gas permeability in the fracture	$k_{FgD} = \frac{k_{Fg}}{k_r}$
dimensionless water permeability in the matrix	$k_{mwD} = \frac{k_{mw}}{k_r}$	dimensionless water permeability in the fracture	$k_{FwD} = \frac{k_{Fw}}{k_r}$
dimensionless gas coefficient of pressure conductivity in the matrix	$\eta_{mgD} = \frac{0.0864 k_{mg}}{\phi_{mg} C_{tmg} \mu_g \eta_r}$	dimensionless water coefficient of pressure conductivity in the matrix	$\eta_{mwD} = \frac{0.0864 k_{mw}}{\phi_{mw} C_{tmw} \mu_w \eta_r}$
dimensionless gas coefficient of pressure conductivity in the fracture	$\eta_{FgD} = \frac{0.0864 k_{Fg}}{\phi_{Fg} C_{tFg} \mu_g \eta_r}$	dimensionless water coefficient of pressure conductivity in the fracture	$\eta_{FwD} = \frac{0.0864 k_{Fw}}{\phi_{Fw} C_{tFw} \mu_w \eta_r}$
dimensionless gas conductivity in the fracture	$C_{FgD} = \frac{w_F k_{Fg}}{k_{mg} L_r} = \frac{k_{FgD} w_{FD}}{k_{mgD}}$	dimensionless gas conductivity in the fracture	$C_{FwD} = \frac{w_F k_{Fw}}{k_{mw} L_r} = \frac{k_{FwD} w_{FD}}{k_{mwD}}$

2.3 Parameter inversion method

Half-length of fracture and permeability of fracture and matrix are the key parameters in the inversion analysis. The idea of using PDA method for parameter inversion is to obtain the measured curve after processing the field data, calculate the theoretical curve according to the established seepage model, and then invert the fracture and matrix parameters by nonlinear fitting the measured curve and theoretical curve. The concrete solution procedure of this method is as follows.

Step 1: Material balance pseudo-time and normalized gas production are introduced to process gas production data, and material balance time and normalized water production are introduced to process water production data, and the production data under the condition of variable production rate and variable BHP is converted to the condition of constant BHP.

The material balance pseudo-time and normalized gas production [19] are defined as follows.

$$t_{ca} = -\frac{G_{pg} c_{tmi}}{q_g} \frac{\mu_{gi} Z_i}{2 p_i} (\psi_i - \psi) \tag{25}$$

$$Nq_g = \frac{q_{sc}}{\psi_i - \psi_{wf}} \tag{26}$$

The material balance pseudo-time and normalized gas production are defined as follows.

$$t_a = \frac{G_{pw}}{q_w} \tag{27}$$

$$Nq_w = \frac{q_w}{p_i - p_{wf}} \tag{28}$$

Step 2: Assuming the initial value of the parameter of inversion, the productivity prediction time is divided into many steps, under each time step:

(1) The model parameters, including gas viscosity, porosity, permeability, compression factor, and compressibility, are updated by the average formation pressure and water saturation.

Different relative permeability curves are used in the matrix and fracture, as shown in the Figure 2.

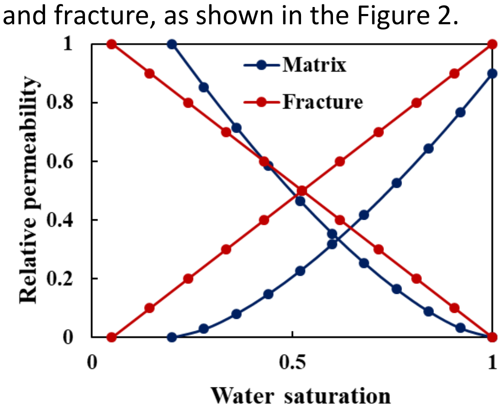

Fig. 2 Relative curves in the matrix and fracture

(2) Gas and water production are calculated according to the formulas (19) and (22) and Stehfest method.

(3) The mass balance equation is used to update the average formation pressure and water saturation.

The average water saturation is calculated as follows.

$$\tilde{S}_w = S_{wi} - \frac{W_p B_w}{V_{mp} + V_{Fp}} \tag{29}$$

The average formation pressure is calculated as follows.

$$\begin{aligned} f(p_a) &= G_p - V_{mp}\left(\frac{V_L p_i}{p_L + p_i} - \frac{V_L \tilde{p}}{p_L + \tilde{p}_m}\right) \\ &-V_{mp}\left(\frac{1-S_{wi}}{B_{gi}} - \frac{1-\tilde{S}_w}{B_{mg}}\right) - V_{Fp}\left(\frac{1-S_{wi}}{B_{gi}} - \frac{1-\tilde{S}_w}{B_{Fg}}\right) = 0 \end{aligned} \tag{30}$$

$$\tilde{p}^{k+1} = \tilde{p}^k - \frac{1}{2^k} \cdot \frac{f(p_a)}{f'(p_a)} \tag{31}$$

Where k is the current time step and k+1 is the next time step.

(4) The production of the next time step is calculated repeatedly to obtain the theoretical curve.

Step 3: The measured curve obtained in step 1 is nonlinear fitted with the theoretical curve obtained in step 2. If the error meets the requirements, the result will be output. Otherwise, the parameters of inversion are taken as initial values and steps 2 and 3 are repeated.

3. *FIELD EXAMPLES*

3.1 Model validation

In this section, the commercial numerical simulation software tNavigator is used to establish a numerical model to verify the accuracy of the inversion method of fracture parameters established after fracturing in deep CBM reservoirs, as shown in Figure 3. The basic model parameters are shown in Table 2. The matrix and fracture are gas-water two-phase seepage in the early stage of production.

Tab. 2 Parameters for model validation

Parameters	Values
Initial formation pressure (MPa)	20
Initial formation temperature (K)	338.15
Length of horizontal well (m)	1000
Number of fracturing segments	10
Reservoir thickness (m)	8
Half-length of fracture* (m)	100
Porosity of matrix (fraction)	0.05
Porosity of fracture (fraction)	0.4
Permeability of matrix* ($10^{-3}\mu m^2$)	0.0001
Permeability of fracture* ($10^{-3}\mu m^2$)	500
Water saturation in the matrix (fraction)	0.5
Water saturation in the fracture (fraction)	0.95

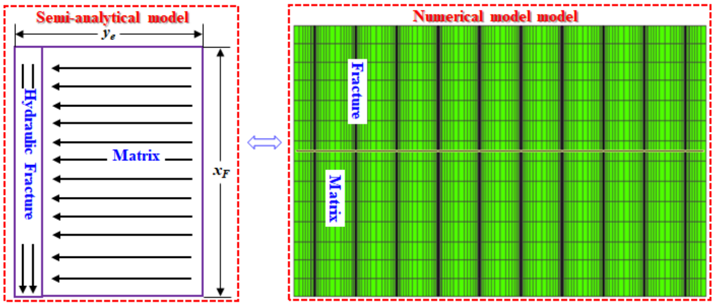

Fig. 3 Schematic of the numerical simulation model

First, the horizontal well is produced under the constant BHP of 2 MPa. The gas and water production of the semi-analytical model and the numerical model are compared to verify the accuracy of the established gas-water two-phase seepage model, as shown in Figure 4. Then the horizontal well is first produced at constant gas production of 6×10^4 m^3/d and then at constant BHP of 2 MPa. The parameter inversion method is used to fit the production data to verify the accuracy of the fracture parameter inversion method during production under the conditions of variable production and BHP. The parameter inversion results are shown in Figure 5 and Table 3. It can be seen from the comparison between the semi-analytical model and the numerical model that the gas and water production curves obtained by the two methods are very consistent, and the normalized gas and water production data have a good fit with the theoretical curves. The interpreted fracture and matrix parameters are basically consistent with the parameters input by the numerical simulation model, and the average relative errors are less than 10%, which is permitted in engineering practice. It is proved that the parameter inversion method of gas-water two-phase in deep CBM reservoirs established in this paper is reliable. And the semi-analytic method proposed in this paper can calculate faster.

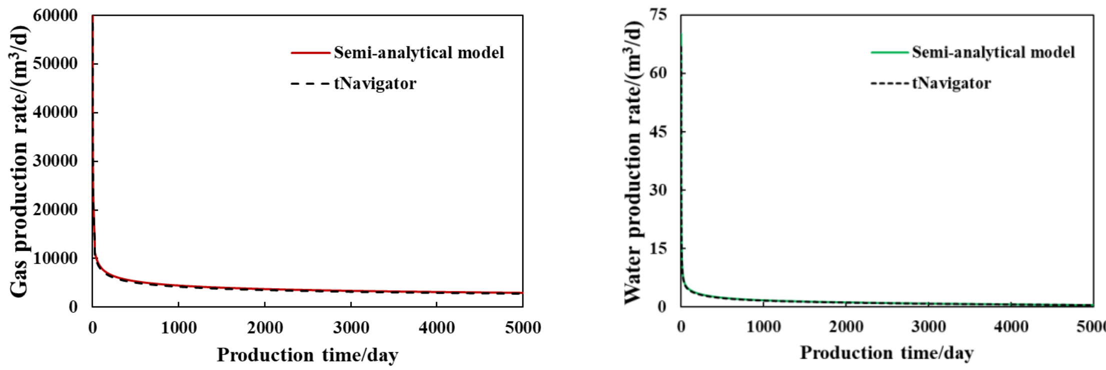

Fig. 4 Comparison of daily gas and water production between the semi-analytical model and tNavigator

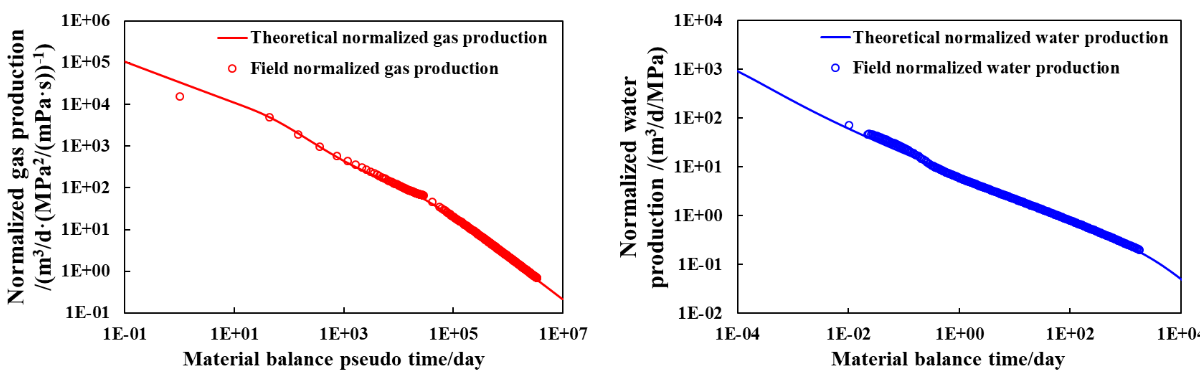

Fig. 5 The matching results between the semi-analytical model and tNavigator

Tab. 3 Parameters interpretation results

Parameters	tNavigator input values	Model inversion values
Half-length of fracture* (m)	100	99.28
Permeability of matrix* ($10^{-3}\mu m^2$)	0.0001	0.000113
Permeability of fracture* ($10^{-3}\mu m^2$)	500	502.75

3.2 Field example

The field data of a deep CBM well in in the northeastern Ordos Basin (China) is analyzed by the established parameter inversion method. The initial temperature and pressure of the reservoir are 338.15 K and 19.4 MPa respectively. The horizontal well is 1000 m long and fractured in 11 stages with 3 clusters in each stage. The parameter inversion method established in this paper is adopted to fit the gas and water production data, and the results are shown in Figure 6 and Table 4. Both charts can get good fitting results in boundary-dominated flow. The daily and cumulative gas and water production data between the field data and semi-analytical model are compared by using the parameters of inversion and the established gas-water two-phase seepage model, and the results are shown in Figure 7 and Figure 8. It can be seen that the daily production and cumulative production of gas and water can all get a good modeling effect, which proves the reliability of the method in field application.

Tab. 4 Parameters interpretation results

Parameters	Values
Half-length of fracture (m)	85.07
Permeability of matrix ($10^{-3}\mu m^2$)	0.000204
Permeability of fracture ($10^{-3}\mu m^2$)	863.66

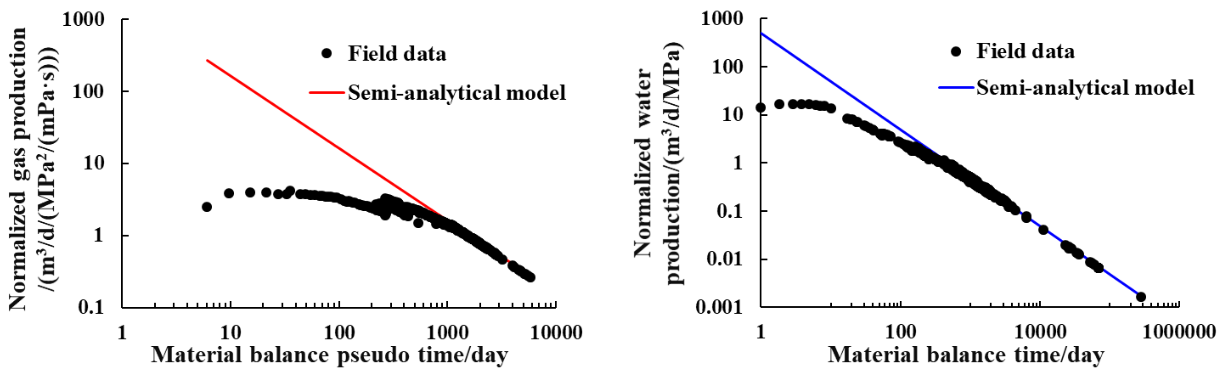

Fig. 6 The matching results between the field data and semi-analytical model

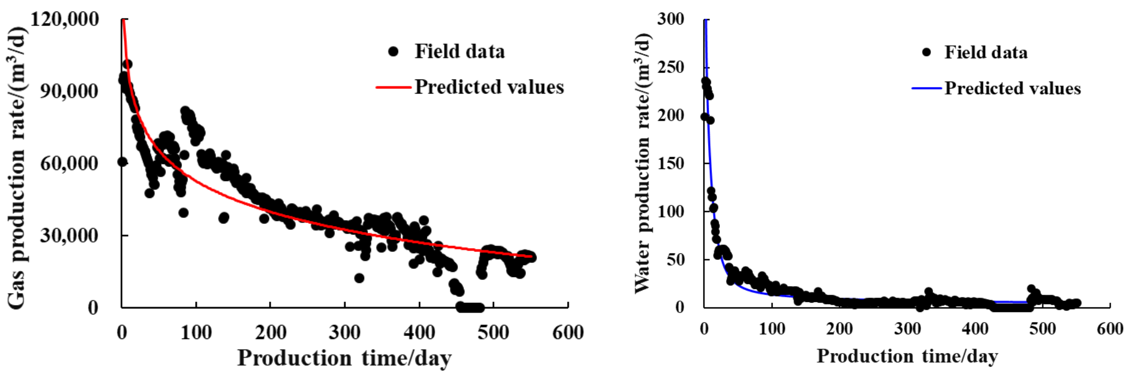

Fig. 7 Comparison of daily gas and water production between the field data and semi-analytical model

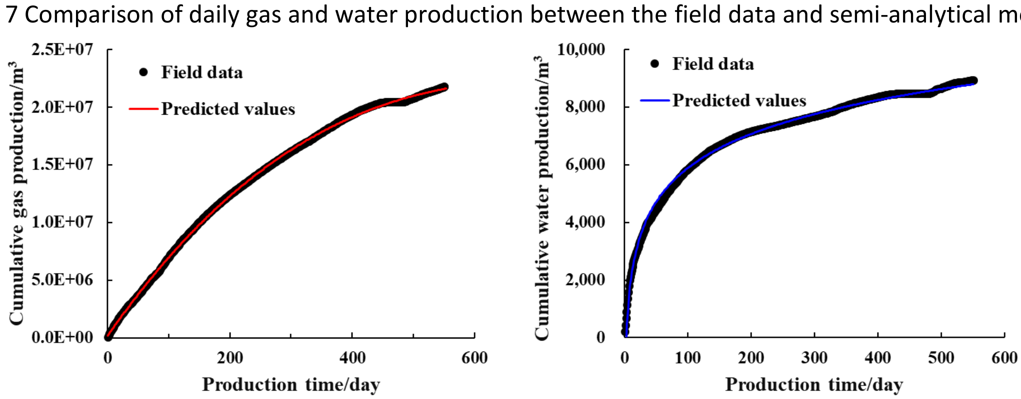

Fig. 8 Comparison of cumulative gas and water production between the field data and semi-analytical model

4. CONCLUSIONS

The major novelty of this study is that a semi-analytical seepage model and parameter inversion method suitable for multi-stage fractured horizontal wells in deep CBM reservoirs is established. The model not only considers the two-phase flow of gas and water in the matrix and fractures, but also considers the complex seepage mechanism of gas and water in the reservoir. By comparing the results of semi-analytic model and commercial numerical simulation, the accuracy of the inversion method is proved. And the semi-analytic method proposed in this paper can calculate faster. Affected by the measurement accuracy of the field data, the duration of the linear section of the boundary control flow is longer and more obvious, and the data at this stage is more suitable for parameter inversion.

ACKNOWLEDGEMENT

The work is supported by the National Natural Science Foundation of China (No. 51974328 and U19B6003-03-05).

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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