Numerical analysis of drainage rate for multilayer drainage coalbed methane well group in Southern Qinshui basin

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Abstract
Multilayer drainage is one of the important technologies for coalbed methane (CBM) production in China. In this study, a multi-field fully coupled mathematical model for CBM production was established to analyze the multilayer drainage of CBM well group in southern Qinshui basin. Based on the numerical simulation results, the characteristics of CBM well production under different drainage rates and key factors influencing the CBM production were further discussed. The results show that the effect of an increased drainage rate on gas production of CBM wells and CBM recovery of No.3 coal seam is not significant. However, it significantly improved the gas production of CBM wells and CBM recovery of No.15 coal seam. After a long period of production, the CBM content in No.3 coal seam has reduced to a low level and the pressure drop potential of No.3 coal seam is insignificant, which are important reasons for the insignificant increase of CBM production even under a drainage rate of 2 to 7 times. Conversely, No.15 coal seam has larger residual CBM content and increasing the drainage rate can significantly improve the pressure drop and superimposed well interference of No.15 coal seam, which means No.15 coal seam has greater production potential than No.3 coal seam. Therefore, it is recommended to improve the gas production and CBM recovery in No.15 coal seam by increasing the drainage rate.

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rate, and the average hydraulic pressure drop should be 0.018–0.031 MPa/day. The influence of effective stress is weak in No.3 and No.15 coal seam, and the coal seam permeability is largely influenced by the shrinkage of coal matrix caused by CBM desorption. This indicates the feasibility of increase in gas production from CBM wells by increasing the drainage rate.

Keywords
Multilayer drainage, gas production, coalbed methane recovery, numerical simulation, Qinshui basin

Introduction
The international energy agency (IEA) estimates that there are $2.638 \times 10^{14}$ m$^3$ of coalbed methane (CBM) in the world, and the exploitation and utilization of CBM has been carried out in more than 30 countries (Lau et al., 2017; Li et al., 2018). China is rich in CBM resources and has a broad development prospect. After more than 20 years of continuous exploration, great progress has been made in terms of exploration and exploitation technology (Tao et al., 2019a, 2019b). Compared with the United States, Canada and Australia, where CBM development has been successful, China’s coal reservoirs are characterized by low permeability and strong heterogeneity (Qin et al., 2018; Zhang et al., 2015), which indicates that China’s CBM well drainage technology cannot completely replicate the foreign experience.

The achievements of CBM drainage technology are mainly concentrated in the multilayer fracturing, the layered fracturing, and the multilayer drainage technology of the multi-seam, and the multi-branch horizontal well drainage technology (Chen et al., 2019; Ren et al., 2014). Correspondingly, the multilayer drainage technology of CBM in China is still shallow, and most of them are qualitative analysis (Mu et al., 2009; Qin et al., 2014; Zhang et al., 2011). The multilayer drainage parameters of CBM well are mainly affected by the properties of surrounding rocks, fluid supply capacity of coal reservoir, pressure gradient, the distance of coal seams, initial permeability, and fracture permeability after fracturing (Ni et al., 2010; Wang et al., 2019). Drainage rate is one of the most important parameters of multilayer drainage, and has a great influence on the gas production of CBM wells. If the drainage rate of CBM well is large, the fluid (water and free methane) near the wellbore flows to the wellbore at a relatively high speed with a relatively large fluid pressure difference, thus instantly reducing the fluid pressure in the coal fractures (Zhao et al., 2008). In this process, the effective stress increases rapidly, causing the coal fractures to close (Chen et al., 2019b; Zhang et al., 2019). Therefore, the inability to effectively extend the pressure drop and drainage radius makes it impossible for the long-term sustained production from the CBM well (Chen et al., 2019b; Zhang et al., 2019; Zhao et al., 2008). Furthermore, during multilayer drainage, coal seams exhibit pressure differences, which can lead to mutual interference, and not all coal seams have the capacity to contribute to fluid supply (Chen et al., 2018; Ni et al., 2010; Yang et al., 2019). These factors further increase the difficulty of controlling production in multilayer drainage CBM wells.

Although, the multilayer drainage technology has been successfully applied to CBM well production, there are many practical limitations. Due to the complicated geological
conditions of coal seams in China, it is only applied in a small number of CBM blocks, e.g., Tiefa block in northeast of China, Panjiang block in southwest of China. The multilayer drainage technology has been implemented in Qinshui basin for a short time. A number of multilayer drainage CBM wells have been carried out in No. 3 and No. 15 coal seam in southern Qinshui basin in the past three years. The lack of engineering practice leads to its weak implementation. That’s why it is usually studied by well test analysis and physical simulation (Wang and Qin, 2019; Wu et al., 2018). In view of the long experiment period and high experiment cost involved with physical simulation, the physical simulation is not comprehensive enough. Numerical simulation is usually applied to the formulation and optimization of CBM well production system. Numerical simulation is a key technology to study the laws of CBM storage, transportation, and accumulation (Kang et al., 2019; Zhao et al., 2019), and also to explain the coal seam parameters, formulate the CBM well production system, and predict CBM production (Fan et al., 2018a; Sun et al., 2018). However, the numerical simulation of CBM well multilayer drainage is at its early stages and requires further analyses to understand the involved mechanism and key engineering parameters such as drainage rate.

In this study, taking a CBM well group in the Fanzhuang block, southern Qinshui basin as an example, a multi-physical field fully coupled mathematical model for CBM production was established to study the effect of drainage rate on production of multilayer drainage CBM wells. Based on the numerical simulation results, the key factors influencing the CBM production were further discussed. This study is conducive to various mechanisms of multilayer drainage technology, and has important theoretical and practical significance for guiding the engineering practices of multilayer drainage of CBM well.

The fully coupled mathematical model for CBM production

Assumptions

In this study, a multi-physical field fully coupled mathematical model was defined to describe coal seam deformation, fluid flow, and energy transmission and conversion in coal seam during CBM exploitation (Xia et al., 2015; Zhang et al., 2008). The mathematical model is established based on the following assumptions (Guo et al., 2015; Li et al., 2016; Wu et al., 2010a; Zhu et al., 2011): (1) coal is a homogeneous elastic medium with “dual-porosity” composed of matrix and fractures; (2) the fractures are saturated with CH\textsubscript{4} and water; (3) CH\textsubscript{4} exists and migrates in pores and fractures, and water exists and migrates in fractures; (4) the adsorption, desorption, and diffusion of CH\textsubscript{4} mainly occur in matrix; (5) CH\textsubscript{4} adsorption and desorption follows Langmuir’s law, and CH\textsubscript{4} diffusion follows Fick’s law; (6) the migration of CH\textsubscript{4} and water in fractures follows the Darcy’s law; (7) the coal deformation conforms the small elastic deformation, and the gas adsorption, desorption and pressure changes will cause changes in volumetric strain of coal (Fang et al., 2019a; Kumar et al., 2014; Langmuir et al., 1916; Wang et al., 2018a, 2018b).

Numerical model

Stress equation of coal seam. Considering the thermal expansion/contraction strain, the strain caused by the pore and fracture pressure, and the contraction/expansion strain caused by the CH\textsubscript{4} desorption/adsorption, the constitutive equation of stress field of non-
where, $\varepsilon_{ij}$ is the strain tensor component, m; $\sigma_{ij}$ is the stress tensor component; $G$ is the shear modulus, GPa, $G = D / [2(1 + v)]$; $D$ is the effective elasticity modulus, Pa; $D = 1/[E + 1/(aKn)]$; $v$ is the poisson’s ratio; $E$ is the elastic modulus, GPa; $a$ is the matrix width, m; $K_n$ is the fracture stiffness, Pa/m; $K$ is the bulk modulus of coal, GPa, $K = D / 3(1 - 2v)$; $\sigma_{kk}$ is the normal stress component; $\delta_{ij}$ is the Kronecker symbol; $\alpha_T$ is the thermal expansion coefficient, K$^{-1}$; $T$ is the coal seam temperature, K; $T_0$ is the initial temperature of coal seam, K; $\alpha_m$ is the Biot effective-stress coefficient of coal matrix, MPa; $K_s$ is the bulk modulus of coal matrix, Pa; $P_m$ is the pressure in matrix, Pa; $P_f$ is the pressure in fracture, Pa; $\varepsilon_a$ is the matrix contraction strain caused by CH$_4$ desorption, kg/m$^3$; $V_{sg}$ is the adsorbed CH$_4$ content, m$^3$/kg; $i$ and $j$ represent the direction of $x$ axis, $y$ axis and $z$ axis, $i = x, y, z$, $j = x, y, z$.

The pressure in coal fractures can be defined as follows (Li et al., 2016; Rutqvist et al., 2002)

$$P_f = S_w P_{fw} + (1 - S_w) P_{fg}$$

where, $P_{fw}$ is the water pressure in fracture, Pa; $P_{fg}$ is the gas pressure in fracture, Pa; $S_w$ is the water saturation; $S_g$ is the gas saturation.

The adsorbed CH$_4$ content in coal follows the improved Langmuir equation (Li et al., 2016; Zhu et al., 2011)

$$V_{sg} = \frac{V_L P_m}{P_L + P_m} \exp \left[ -\frac{d_2}{1 + d_1 P_m} (T - T_t) \right]$$

where, $d_1$ is the pressure coefficient, Pa$^{-1}$; $d_2$ is the temperature coefficient, K$^{-1}$; $V_L$ is the Langmuir volume constant, m$^3$/kg; $P_L$ is the Langmuir pressure constant, Pa; $T_t$ is the temperature of coal adsorption/desorption experiment, K.

The Cauchy theorem can be used to represent the relationship between coal seam strain and displacement (Cui et al., 2018; Fan et al., 2018b, 2019a,b; Sang et al., 2016), which can be defined as follows

$$\varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i})$$

where, $u_{i,j}$ and $u_{j,i}$ are the displacements in the $(i, j)$ and $(j, i)$ directions, respectively.
The stress equilibrium equation in coal can be defined as follows (Cui et al., 2018; Fan et al., 2018b; Sang et al., 2016)

$$\sigma_{ij} + f_i = 0$$  \hspace{1cm} (5)

where, $f_i$ is the volumetric stress in the $i$ direction.

According to the equations (1) to (5), the improved stress equation of coal seam during CBM production can be defined as follows

$$Gu_{iijj} + \frac{G}{1 - 2\nu} u_{ij} + f_i = K\alpha \tau \Delta T_{ij} + \alpha_m P_{m,i} + \alpha_f P_{f,i} + K\kappa_{a,i}$$  \hspace{1cm} (6)

**Fluid migration equation.** The CH$_4$ migration in matrix is mainly controlled by its concentration. In the initial stage, the gas pressure in matrix is equal to the gas pressure in fracture. After CBM well production, CH$_4$ adsorbed in matrix gradually desorbs and migrates into the fracture due to the influence of concentration difference. According to the Fick's law, the CH$_4$ mass conservation equation in matrix can be defined as follows (An et al., 2013; Li et al., 2016; Xia et al., 2015)

$$\frac{\partial m_m}{\partial t} = -\frac{M_g}{\tau RT} (P_m - P_{f_g})$$  \hspace{1cm} (7)

where, $m_m$ is the CH$_4$ content in matrix per unit volume, kg/m$^3$; $M_g$ is the CH$_4$ molar mass, kg/mol; $R$ is the gas molar constant, $R = 8.314$J/mol/K; $\tau$ is the desorption time of CH$_4$, s.

CH$_4$ in matrix is composed of the adsorbed CH$_4$ and the free CH$_4$, which can be defined as follows (Ren et al., 2017; Wang et al., 2018a, 2018b; Yin et al., 2017)

$$m_m = V_{sg} \rho_s \frac{M_g}{RT} P_s + \phi_m \frac{M_g}{RT} P_m$$  \hspace{1cm} (8)

where, $\rho_s$ is the density of coal matrix, kg/m$^3$; $P_s$ is the standard atmospheric pressure, 101325 Pa; $T_s$ is the standard temperature, 298.15 K; $\phi_m$ is the matrix porosity.

According to the equations (3), (7), and (8), CH$_4$ migration equation in matrix during CBM well production can be defined as follows

$$\frac{\partial}{\partial t} \left\{ \frac{V_L P_m}{P_L + P_m} \exp \left[ -\frac{d_2}{1 + d_1 P_m} (T - T_i) \right] \rho_s \frac{M_g}{RT_s} P_s + \phi_m \frac{M_g}{RT} P_m \right\} = -\frac{M_g}{\tau RT} (P_s - P_{f_g})$$  \hspace{1cm} (9)

During CBM well production, CH$_4$ in matrix continuously provides mass sources for CH$_4$ in fracture. Therefore, CH$_4$ mass conservation equation in fracture can be defined as follows (Li et al., 2016; Xu et al., 2014)

$$\left\{ \begin{array}{l}
\frac{\partial}{\partial t} (S_{w} \phi_f \rho_w) + \nabla (\rho_w u_w) = 0 \\
\frac{\partial}{\partial t} (S_{g} \phi_f \rho_g) + \nabla (\rho_g u_g) = (1 - \phi_f) \frac{M_g}{\tau RT} (P_m - P_{f_g})
\end{array} \right.$$  \hspace{1cm} (10)
where $\phi_f$ is the porosity in fracture; $t$ is time, s; $u_w$ and $u_g$ are the migration velocity of water and CH$_4$, respectively, m/s.

Water density is closely related to temperature, which can be defined as follows

$$\rho_w = c(T - T_s) + \rho_{ws}$$

where, $c$ is the temperature coefficient of water, kg/(m$^3$·K); $\rho_{ws}$ is water density in the standard state, kg/m$^3$.

Based on the Darcy’s law, the water-gas two-phase velocity in fractures can be defined as follows (Li et al., 2016; Xu et al., 2014)

$$\begin{cases}
  u_w = \frac{kk_{rg0}k_{rg}}{\mu_w} \nabla P_{fw} \\
  u_g = \frac{kk_{rg0}k_{rg}}{\mu_g} \left(1 + \frac{b_1}{P_{fg}}\right) \nabla P_{fg}
\end{cases}$$

where, $k$ is the absolute permeability of coal, m$^2$; $k_{rg0}$ and $k_{rw0}$ are the relative permeability of CH$_4$ and water in endpoint, respectively; $k_{rg}$ and $k_{rw}$ are the relative permeability of CH$_4$ and water, respectively; $\mu_g$ and $\mu_w$ are the dynamic viscosities of CH$_4$ and water, respectively; $b_1$ is the Klingenberg factor, Pa.

The relative permeability of CH$_4$ and water is defined as follows (Li et al., 2016; Xu et al., 2014)

$$\begin{align*}
  k_{rw} &= \left(\frac{S_w - S_{w*}}{1 - S_w}\right)^4 \\
  k_{rg} &= \left[1 - \left(\frac{S_w - S_{w*}}{1 - S_w}\right)^2\right] \left[1 - \left(\frac{S_w - S_{w*}}{1 - S_w}\right)^2\right]
\end{align*}$$

where, $S_{w*}$ is the irreducible water saturation; $S_{gr}$ is the residual gas saturation.

The relationship between CH$_4$ pressure and water pressure can be defined as follows

$$P_{fw} = P_{fg} - P_{cgw}$$

where, $P_{cgw}$ is capillary force, Pa.

The CH$_4$ and water migration equation during CBM well production can be deduced by substituting equations (11) to (14) into (10).

$$\frac{\partial}{\partial t} \left(S_g \phi_f \frac{M_g}{RT} P_{fg}\right) + \nabla \left[-\frac{M_g kk_{rg0}k_{rg}}{RT} \frac{1}{\mu_g} (P_{fg} + b_1) \nabla P_{fg}\right] = (1 - \phi_f)(P_m - P_{fg}) \frac{M_g}{\tau RT}$$

$$\frac{\partial}{\partial t} \left(S_w \phi_f [c(T - T_s) + \rho_{ws}]\right) + \nabla \left[-[c(T - T_s) + \rho_{fg}] \frac{kk_{rg0}k_{rw}}{\mu_w} \nabla P_{fw}\right] = 0$$
Energy conservation equation. Assuming that there is a thermal equilibrium state between the fluid and coal, the thermal equilibrium state can be expressed as follows (Fan et al., 2018b; Lin et al., 2017; Wang et al., 2017).

\[
\frac{\partial}{\partial t} \left[(\rho C_p)_{\text{eff}} T\right] + \eta_{\text{eff}} \nabla T - \nabla (\lambda_{\text{eff}} \nabla T) + \alpha_T K_s \frac{\partial \epsilon_v}{\partial t} + q_{st} \frac{\rho_s \rho_g g V_{sg}}{M_g} \frac{\partial V_{sg}}{\partial t} = 0
\]

(17)

where, \((\rho C_p)_{\text{eff}}\) is effective specific heat capacity of coal, \(\text{J/(m}^3\cdot\text{K)}\); \(\eta_{\text{eff}}\) is effective convection coefficient of gas-water mixture, \(\text{J/(m}^2\cdot\text{s)}\); \(\lambda_{\text{eff}}\) is effective thermal conductivity, \(\text{W/(m}\cdot\text{K)}\); \(\epsilon_v\) is volumetric strain of coal seam; \(q_{st}\) is adsorption heat of CH\(_4\), \(\text{kJ/mol}\).

The five terms on the left of equation (17) represent internal energy, heat convection and heat conduction between coal and fluid, strain energy of coal matrix, and gas adsorption energy, respectively.

Where,

\[
(\rho C_p)_{\text{eff}} = (1 - \phi_f - \phi_m) \rho_s C_s + (S_g \phi_f + \phi_m) \rho_g C_g + S_w \phi_f \rho_w C_w
\]

(18)

\[
\eta_{\text{eff}} = -\frac{k k_{r00} k_{rg}}{\mu_g} \left(1 + \frac{b_1}{P_{f0}}\right) \nabla P_{f0} \hat{\lambda}_s - \frac{k k_{r00} k_{rw}}{\mu_w} \nabla P_{w0} \hat{\lambda}_w
\]

(19)

\[
\lambda_{\text{eff}} = (1 - \phi_f - \phi_m) \lambda_s + (S_g \phi_f + \phi_m) \lambda_g + S_w \phi_f \lambda_w
\]

(20)

where, \(C_g, C_w\) and \(C_s\) are the specific heat capacities of CH\(_4\), water, and coal matrix, respectively, \(\text{J/(kg} \cdot \text{K)}\); \(\hat{\lambda}_g, \hat{\lambda}_w\) and \(\hat{\lambda}_s\) are the thermal conductivity of CH\(_4\), water, and coal matrix, respectively, \(\text{W/(m} \cdot \text{K)}\); \(q_{st}\) is the equal volume adsorption heat, \(\text{kJ/mol}\).

Dynamic equation of porosity and permeability. Porosity and permeability are the key factors that affect CH\(_4\) and water migration. The porosity in matrix can be defined as follows (Cui and Bustin, 2005; Li et al., 2016; Palmer and Mansoori, 1998; Zhang et al., 2008)

\[
\phi_m = \frac{1}{(1 + S) \phi_{m0}} \left[(1 + S_0) \phi_{m0} + \alpha_m (S - S_0)\right]
\]

(21)

where,

\[
\begin{cases}
S = \epsilon_v + \frac{P_m}{K_s} - \alpha_T (T - T_0) - \epsilon_a \\
S_0 = \epsilon_{v0} + \frac{P_{m0}}{K_s} - \epsilon_{a0}
\end{cases}
\]

(22)

where, \(\epsilon_v\) is the volumetric strain of the coal; the subscript “0” represents the initial state.
The porosity in fracture can be defined as follows (Li et al., 2016; Wu et al., 2010a)

$$
\phi_f = \phi_{f0} - \frac{3\phi_{f0}}{\phi_{f0} + 3K_f/K} \left[ \alpha_f(T - T_0) + (\epsilon_a - \epsilon_{a0}) - (\epsilon_v - \epsilon_{v0}) \right] 
$$

(23)

where, $K_f$ is the modified fracture stiffness, $K_f = aK_m$, N/m.

There is a cube law between coal permeability and porosity. Therefore, the permeability can be defined as follows (Li et al., 2016; Palmer and Mansoori, 1998; Pan and Connell, 2007; Wu et al., 2010b; Wang et al., 2018a, 2018b)

$$
k = k_0 \left( 1 - \frac{3}{\phi_{f0} + 3K_f/K} \left[ \alpha_f(T - T_0) + (\epsilon_a - \epsilon_{a0}) - (\epsilon_v - \epsilon_{v0}) \right] \right)^3
$$

(24)

where, $k_0$ is the initial permeability of coal seam.

**Full coupling relationships of multiple physical fields**

In conclusion, equations (6), (9), (15) to (17) constitute the fully coupled mathematical model of CBM production. In this study, the mathematical model was solved by finite element method using the COMSOL Multiphysics simulation software.

In the mathematical model, the full coupled relationship between the physical fields is shown as follows: (1) the thermal stress caused by the change of coal seam temperature has an impact on the stress field of coal seam; (2) the strain energy and heat transfer generated by energy dissipation in coal affect the coal seam temperature; (3) the change of temperature has an impact on the gas adsorption/desorption and the gas/water density; (4) the thermal convection, heat conduction, and gas adsorption/desorption affect the coal seam temperature; (5) the change in porosity and permeability caused by coal deformation has an impact on gas/water flow; (6) the change in gas/water pressure causes coal deformation.

**Numerical simulation process**

**Engineering well group**

A CBM well group named as FZ well group in the Fanzhuang block in southern Qinshui basin is selected as the research object. There are 12 vertical CBM wells in the FZ well group (Figure 1(a)), including 5 old single-layer drainage wells (i.e., FZ-1, to FZ-5) which have produced for 4054 days, 4 new single-layer drainage wells (i.e., FZ-6 to FZ-9) which have produced for 230 days, and 3 new multilayer drainage wells (i.e., FZ-10, to FZ-12) which have produced for 1750 days. The single-layer drainage wells only produce CH$_4$ from No.3 coal seam of Shanxi formation, while the multilayer drainage wells produce CH$_4$ form both No.3 coal seam of Shanxi formation and No.15 coal seam of Taiyuan formation (Figure 1 (b) and (c)).

Considering the calculation capability of the computer, the numerical simulation was carried out in an area of 1000 m $\times$ 900 m ($x \times y$) in the horizontal direction (Figure 1(b) and (c)). The average thickness of No.3 and No.15 coal seam within FZ well group is 7.0 m and 3.5 m, respectively, and the diameter of the wellbore is 0.1 m. The average distance between
No.3 and No.15 coal seam is 100 m, and No.3 coal seam lies above No.15 coal seam (Figure 1(b) and (c)).

**Key parameters**

The key parameters for the numerical simulation are mainly derived from engineering data of FZ well group, experimental data of coal samples collected from #3 coal seam of southern Qinshui basin, and data published by other scholars (Fan et al., 2018b; Fang et al., 2019a, 2019b; Shi et al., 2008; Zhou et al., 2016). The key parameters are shown in Table 1.

**Numerical simulation cases**

The numerical simulation cases, initial conditions, and boundary conditions are shown in Table 2. The numerical simulation process involves two steps.

**Step 1.** The initial pressure condition is set to the initial pressure of No.3 and No.15 coal seams. The internal boundary conditions are the flowing bottom hole pressure (FBHP) of the 12 CBM wells, and other boundaries are set as constant pressure boundary, whose pressure is the initial pressure of coal seam (Table 2). The history fitting results are used to verify the accuracy of the mathematical model and invert the coal seam parameters.

**Step 2.** The initial condition is set to the coal seam pressure after 4054 days of production (Table 2). The internal boundary conditions are the FBHP of the 12 CBM wells under actual drainage rate, and 2, 5, and 7 times drainage rate than actual situation of 12 CBM wells (Table 2). Other boundaries are set as constant pressure boundary like Step 1.

It’s important to note that the drainage rate of CBM wells is mainly realized by adjusting FBHP drop. While the water production stage of CBM well involves no casing pressure and an equal FBHP and hydraulic pressure, the gas production stage involves the release of casing pressure to a lower level in a short time, and FBHP is controlled by hydraulic pressure in a longer time. Therefore, in this study, drainage rate of CBM wells is controlled by hydraulic pressure. The 2, 5, and 7 times higher drainage rate than actual situation of 12 CBM wells means hydraulic pressure decreased by 2, 5, and 7 times than the actual situation of 12 CBM wells, respectively. The hydraulic pressure drops applied in the numerical simulation are shown in Table 3. After hydraulic pressure drops to 0.2 MPa, it will be kept constant.
Table 1. Key parameters for numerical simulation.

| Parameters                                      | No.3 coal seam | No.15 coal seam | Units     |
|------------------------------------------------|----------------|-----------------|-----------|
| Average thickness of coal seam ($H$)           | 7.00           | 3.50            | m         |
| Initial pressure of coal seam ($P_0$)          | 6.50           | 7.50            | MPa       |
| Initial temperature of coal seam ($T_0$)       | 300            | 303             | K         |
| Matrix porosity ($\phi_m$)                     | 0.040          | 0.045           | –         |
| Fracture porosity ($\phi_f$)                   | 0.010          | 0.015           | –         |
| Fracture permeability ($k_f$)                   | 0.514          | 0.754           | $10^{-3}$ $\mu m^2$ |
| Matrix width ($a$)                              | 0.01           | 0.02            | m         |
| Fracture aperture ($b$)                         | $0.1 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | m       |
| Young's modulus of coal ($E$)                   | 0.713          | 1.414           | GPa       |
| Young's modulus of coal matrix ($E_s$)          | 8.47           | 10.32           | GPa       |
| Fracture stiffness ($K_n$)                      | 2.80           | 2.85            | GPa/m     |
| Thermal expansion coefficient of coal matrix ($x_T$) | $2.4 \times 10^{-5}$ | $2.4 \times 10^{-5}$ | K$^{-1}$ |
| Adsorption strain coefficient ($x_{sg}$)        | 0.06           | 0.06            | kg/m$^3$  |
| Langmuir strain coefficient of CH$_4$ ($x_L$)  | 0.0128         | 0.0128          | –         |
| Langmuir pressure constant of CH$_4$ ($P_L$)   | 2.07           | 2.07            | MPa       |
| Langmuir volume constant of CH$_4$ ($V_L$)     | 0.0256         | 0.0256          | $m^3$/kg  |
| CH$_4$ temperature coefficient ($d_1$)         | 0.021          | 0.025           | K$^{-1}$  |
| CH$_4$ pressure coefficient ($d_2$)            | 0.071          | 0.075           | MPa$^{-1}$ |
| Klingenberg factor ($b_1$)                      | 0.76           | 0.74            | MPa       |
| Adsorption heat of CH$_4$ ($q_{st}$)           | 33.4           | 33.4            | kJ/mol    |
| Temperature coefficient of water ($c$)         | 0.0228         | 0.0228          | kg/(m$^3$·K) |
| Thermal conductivity of coal ($\lambda_c$)     | 0.191          | 0.203           | W/(m·K)   |
| Thermal conductivity of CH$_4$ ($\lambda_g$)   | 0.031          | 0.052           | W/(m·K)   |
| Thermal conductivity of water ($\lambda_w$)    | 0.598          | 0.719           | W/(m·K)   |
| Specific heat capacity of coal matrix ($C_s$)   | 1350           | 1750            | J/(kg·K)  |
| Specific heat capacity of CH$_4$ ($C_g$)       | 2160           | 2360            | J/(kg·K)  |
| Specific heat capacity of water ($C_w$)         | 4200           | 4500            | J/(kg·K)  |

Table 2. The numerical simulation cases.

| Step       | Cases                                      | Time, day | Initial conditions                                      | Boundary conditions                                      |
|------------|-------------------------------------------|-----------|--------------------------------------------------------|----------------------------------------------------------|
| Step 1     | History fitting                           | Actual drainage rate | 4054 | Initial pressure of coal seam                          | (1) Internal boundary conditions are FBHP of CBM wells   |
| Step 2     | CBM well production with different drainage rate | Actual drainage rate | 1800 | (1) Pressure of No.3 coal seam after 4054 days production; (2) Pressure of No.15 coal seam after 1750 days production | (2) The pressure at other boundaries is the initial pressure of coal seam |
History fitting results and model validation

The THM fully coupled mathematical models were verified by history fitting. Figure 2 shows the History fitting results of FZ-1, FZ-6, and FZ-10.

The average fitting errors of daily gas production of 12 CBM wells are in the range of 3.52–17.94%, and the average is 9.56% (Table 4). The average fitting errors of FZ-2, FZ-3, FZ-6, and FZ-10 are the largest, which are larger than 10%, while the average fitting errors of other wells are relatively small (Table 4). The simulated daily gas production is in good agreement with the actual CBM well production data, which verifies the accuracy of the mathematical model.

### Table 3. Exact values of hydraulic pressure drop.

| Well number | Well type        | Hydraulic pressure drops used in numerical simulation, MPa/day |
|-------------|------------------|-------------------------------------------------------------|
|             |                  | Actual  | 2 times | 5 times | 7 times |
| FZ-1        | Old single-layer drainage wells | 0.0016  | 0.0032  | 0.0080  | 0.0112  |
| FZ-2        |                   | 0.0016  | 0.0032  | 0.0080  | 0.0112  |
| FZ-3        |                   | 0.0017  | 0.0034  | 0.0085  | 0.0119  |
| FZ-4        |                   | 0.0017  | 0.0034  | 0.0085  | 0.0119  |
| FZ-5        |                   | 0.0027  | 0.0054  | 0.0135  | 0.0189  |
| FZ-6        | New single-layer drainage wells | 0.0037  | 0.0074  | 0.0185  | 0.0259  |
| FZ-7        |                   | 0.0031  | 0.0062  | 0.0155  | 0.0217  |
| FZ-8        |                   | 0.0034  | 0.0068  | 0.0170  | 0.0238  |
| FZ-9        |                   | 0.0028  | 0.0056  | 0.0140  | 0.0196  |
| FZ-10       | New multilayer drainage wells | 0.0130  | 0.0260  | 0.0650  | 0.0910  |
| FZ-11       |                   | 0.0186  | 0.0372  | 0.0930  | 0.1302  |
| FZ-12       |                   | 0.0201  | 0.0402  | 0.1005  | 0.1407  |

### Table 4. History fitting error statistics of 12 CBM wells.

| Well number | FZ-1 | FZ-2 | FZ-3 | FZ-4 | FZ-5 | FZ-6 |
|-------------|------|------|------|------|------|------|
| Error, %    | 7.46 | 17.94| 14.69| 9.86 | 8.23 | 11.48|
| Well number | FZ-7 | FZ-8 | FZ-9 | FZ-10| FZ-11| FZ-12|
| Error, %    | 3.52 | 8.45 | 5.31 | 12.92| 7.51 | 7.36 |

**History fitting results and model validation**

The THM fully coupled mathematical models were verified by history fitting. Figure 2 shows the History fitting results of FZ-1, FZ-6, and FZ-10.

The average fitting errors of daily gas production of 12 CBM wells are in the range of 3.52–17.94%, and the average is 9.56% (Table 4). The average fitting errors of FZ-2, FZ-3, FZ-6, and FZ-10 are the largest, which are larger than 10%, while the average fitting errors of other wells are relatively small (Table 4). The simulated daily gas production is in good agreement with the actual CBM well production data, which verifies the accuracy of the mathematical model. The fitting error of daily gas production of old single-layer drainage wells are generally larger than new single-layer drainage wells and new multilayer drainage
wells. That is because the drainage system of old single-layer drainage wells is frequently adjusted during the production process, and the gas production greatly fluctuates.

**Results and discussion**

**Gas production under varying drainage rate**

**Gas production of CBM wells.** An increase in drainage rate can effectively increase the daily production of CBM wells (Figure 3). The increase of daily production from new multilayer drainage wells is much larger than that of old single-layer drainage wells and new single-layer drainage wells (Figure 3, Table 5), which means the effect of drainage rate on gas

![Figure 3. Daily gas production of CBM wells in Step 2 under different drainage rate.](image)

| Well number | Well type                        | 2 times | 5 times | 7 times |
|-------------|----------------------------------|---------|---------|---------|
| FZ-1        | Old single-layer drainage wells   | 1.13    | 2.48    | 3.51    |
| FZ-2        |                                  | 1.74    | 4.11    | 5.86    |
| FZ-3        |                                  | 1.30    | 3.00    | 4.24    |
| FZ-4        |                                  | 1.52    | 3.90    | 5.30    |
| FZ-5        |                                  | 1.48    | 3.63    | 5.01    |
| FZ-6        | New single-layer drainage wells   | 1.40    | 5.12    | 6.47    |
| FZ-7        |                                  | 1.41    | 4.93    | 6.44    |
| FZ-8        |                                  | 1.20    | 4.24    | 5.17    |
| FZ-9        |                                  | 1.81    | 4.39    | 6.12    |
| FZ-10       | New multilayer drainage wells     | 14.00   | 40.66   | 52.39   |
| FZ-11       |                                  | 3.14    | 11.14   | 13.92   |
| FZ-12       |                                  | 2.71    | 10.55   | 13.60   |

Table 5. Average increase of cumulative gas productions of CBM wells in Step 2.
production is comparatively more significant in multilayer drainage wells. Compared to the
gas production under actual drainage rate, the upsurge in gas production of CBM wells
under 5 times and 7 times drainage rates were significantly higher than those under 2 times
drainage rates (Figure 3). However, Except FZ-10, the differences in increase of daily gas
production and cumulative daily gas production of CBM wells under 5 times and 7 times
drainage rates are relatively small, which are around 1–2% (Table 5). This indicates that the
larger the gap in drainage rate, the more significant is the increase in gas production. The 5
times drainage rate reaches the upper limit of the stimulation effect on gas production, and
then the effect of drainage rate on gas production is no longer significant. Considering the
effect of effective stress and velocity sensitivity, the increased drainage rate should not be
larger than 5 times, which means the average hydraulic pressure drop should not be larger
than 0.031 MPa/day.

**CBM recovery of coal seam.** In Step 1, the CBM recovery increased significantly, and the rate
of increase gradually reduced with production time (Figure 4). The areas with larger CBM
recovery are mainly located near the production well, and the CBM recovery gradually
reduces as we move further away from the production well (Figure 4). Due to the long
production time and multiple single-layer drainage wells, a large amount of CBM has been

![Figure 4. CBM recovery of coal seam in Step 1.](image-url)
produced from No.3 coal seam, and the CBM recovery in the well group has reached a range of 50–60% (Figure 4). Before the production of new single-layer drainage wells and new multilayer drainage wells, the CBM recovery in No.3 coal seam of 5 old single-layer drainage wells has reached about 30% (Figure 4). While, the 5 new multilayer drainage wells have a shorter production time of only 1750 days, and the CBM recovery in No.15 coal seam is only 10–20% in a small area around the wellbore (Figure 4).

In Step 2, since the CBM recovery of No.3 coal seam in Step 1 was relatively large, the effect of increasing drainage rate on the CBM recovery is not obvious (Figure 5(a)). Compared to the CBM recovery under actual drainage rate, there is a small increase in CBM recovery of No.15 coal seam in Step 2 under 2 to 7 times drainage rates (Figure 5(b)). The CBM recovery shows slight increase with the increase of drainage rate, and the differences among CBM recoveries under different drainage rates are concentrated within 100 m of the wellbore (Figure 5(b)).

The key factors influencing the stimulation effect of CBM

Pressure reduction of coal seam. The coal seam pressure gradually decreases with the increase of CBM well production time, and decreases significantly at Step 1 (Figure 6). Due to the larger number of CBM wells and longer production times, No.3 coal seam formed a more significant well interference than No.15, which means the decrease in coal seam pressure is larger in No.3 coal seam (Figure 6).

In Step 2, the increasing drainage rate can accelerate the reduction of coal seam pressure far away from the wellbore. However, due to the great reduction of the pressure of No.3 coal seam in Step 1 (generally decrease to 3 MPa), the increase in pressure drop under the influence of different drainage rates is not significant (Figure 7(a)). Compared to the well interference under actual drainage rate, well interference of No.15 coal seam in Step 2 under 2 to 7 times drainage rates is more significant (Figure 7(b)). Since there are only 3 CBM wells in No.15 coal seam, the influence of pressure drop is not wide-spread, the degree of superposition of well interference under different drainage rates is not significant, and the varying

Figure 5. CBM recovery of coal seam in Step 2 under different drainage rate. (a) CBM recovery of No.3 coal seam; (b) CBM recovery of No.15 coal seam.
Figure 6. Coal seam pressure in Step 1.

Figure 7. Coal seam pressure in Step 2 under different drainage rate.
Notes, a, CBM recovery of No.3 coal seam; b, CBM recovery of No.15 coal seam.
drainage rate is effective within a range of 50–80 m around the wellbore (Figure 7(b)). It indicates that large drainage rates can accelerate the formation of superimposed well interference of No.15 coal seam, however, the scope of superimposed well interference is mainly within a range of 100 m around the wellbore in current CBM production situation.

It is indicated by comparison of Figure 4 and Figure 6, and Figure 5 and Figure 7 that the CBM recovery is in good agreement with the coal seam pressure under different drainage rates, which means coal seam pressure has significant influence on CBM production and recovery. The coal seam pressure influences the gas production of CBM wells through superimposed well interference, which is known to increase CBM well production by promoting coal seam pressure decrease and gas desorption. The essence of promoting CBM well production by increasing drainage rate is that a larger drainage rate can accelerate the reduction of coal seam pressure, effectively promote the expansion of well interference and the formation of superimposed well interference.

Due to a long duration of production of the old single-layer drainage wells in No.3 coal seam (4054 days) before the new single-layer drainage wells and new multilayer drainage wells are put into operation, the superimposed well interference has been expanded effectively, and the coal seam pressure has been reduced to a certain level which is about 3 MPa. This has resulted in the effective reduction of coal seam pressure under actual drainage rate, after the new single-layer drainage wells and new multilayer drainage wells are put into operation. In addition, the FZ well group has a dense well distribution, which promotes the formation of superimposed well interference. Therefore, the stimulation effect of increasing drainage rate on gas production of CBM wells and CBM recovery from No.3 coal seam is not significant, and an optimal gas production can be obtained by actual drainage rate and hydraulic pressure drops.

After the new multilayer drainage wells are put into operation, the pressure of No.15 coal seam begins to decrease. Therefore, the pressure of No.15 coal seam has not been effectively decreased. Thus, increasing the drainage rate can significantly improve the magnitude of pressure drop, and promote the formation of superimposed well interference and gas desorption in No.15 coal seam, which can significantly enhance gas production of the new multilayer drainage wells.

Exploring potential of CBM. The initial CBM content in a coal seam is a prerequisite for increasing CBM well production. A large CBM content in a coal seam means great potential for CBM well production. After a long period of production in Step 1, the CBM content in No.3 coal seam has dropped to a low level, which is 12 m³ (STP)/t in the area 100 m around the wellbore and 16 m³ (STP)/t in the area beyond 100 m away from the wellbore (Figure 8). Although increasing the drainage rate can accelerate the reduction of the gas content in No.3 coal seam (Figure 9(a); the area 100 m around the wellbore has generally dropped to less than 8 m³ (STP)/t after 4414 day), exploring potential of CBM is small, which is an important indicator for the insignificant increase of gas production from CBM wells in No.3 coal seam.

The production duration of the 3 new multilayer drainage wells in No.15 coal seam is relatively short, and the gas content reduction in the coal seam is mainly concentrated in an area less than 100 m around the wellbore. On the one hand, it is confirmed that the gas produced by 3 new multilayer drainage wells are mainly CBM from No.3 coal seam. On the other hand, it indicates that the No.15 coal seam has greater CBM exploration potential.
Figure 8. CBM content of coal seam in Step 1.

Figure 9. CBM content of coal seam in Step 2 under different drainage rate. (a) CBM recovery of No.3 coal seam; (b) CBM recovery of No.15 coal seam.
The gas content of No.15 coal seam can be efficiently decreased by increasing the drainage rate (Figure 9(b)).

**Permeability of coal seam.** With the output of CBM, the permeability of coal seam generally increases (Figure 10). However, the observed increase is relatively low, which is generally 5–10% (Figure 10). It indicates that the effective stress is weak in No.3 and No.15 coal seam, and the permeability of the coal seam is mainly controlled by the shrinkage of coal matrix induced by the desorption of CBM. (Figure 10).

Based on the characteristics of gas production, coal seam pressure, CBM recovery and permeability, the 3 new multilayer drainage wells (i.e., FZ-10, FZ-11, and FZ-12) mainly produce the CBM in No.3 coal seam. The CBM in No.15 coal seam has not been extensively produced. That’s why the permeability increase of No.15 coal seam (less than 5%) is smaller than No.3 coal seam (5–10%), and No.15 coal seam is still in the stage of coal seam pressure reduction (Figure 10).

In Step 2, the effect of increasing drainage rate on permeability of No.3 coal seam is not obvious (Figure 12(a)), while the permeability increase under 2 to 7 times drainage rates is slightly larger than that under actual drainage rate (Figure 11(b)). The permeability of coal seam is mainly affected by the shrinkage effect of coal matrix and the effect of effective stress.

![Figure 10. Coal seam permeability in Step 1.](image-url)
during CBM well production. In order to further clarify the relationship between coal seam permeability and effective stress, the water permeability and gas permeability of coal samples under different confining pressures were carried out. The coal samples were collected from coal mine near the FZ well group, and air-dried which means there is no free water in coal samples.

When the effective stress increases from 1 MPa to 2 MPa, the water permeability decreases rapidly from \(0.48 \times 10^{-3} \text{ m}^2\) to \(0.18 \times 10^{-3} \text{ m}^2\). However, beyond an effective stress of 2 MPa, with the increase of effective stress, the rate of decrease in water permeability reduces significantly (Figure 12(a)). This indicates that the control of effective stress on permeability is observed mainly during the initial stage of coal seam pressure reduction which corresponds to early stage, e.g., water production stage, of CBM well production. The control of effective stress on permeability gradually weakens with the incremental reduction

![Figure 11](image1.png)

**Figure 11.** Coal seam permeability in Step 2 under different drainage rate. (a) CBM recovery of No.3 coal seam; (b) CBM recovery of No.15 coal seam.

![Figure 12](image2.png)

**Figure 12.** Water and gas permeability of coal samples under different confining pressures. (a) water permeability of coal samples; (b) gas permeability of coal samples under confining pressures 1.0-3.0 MPa; (c) gas permeability of coal samples under confining pressures 1.0-2.5 MPa and gas input pressure 1.03 MPa.
in coal seam pressure and the concomitant desorption induced matrix shrinkage. Similarly, when the effective stress increases from 1 MPa to 2.5 MPa, the gas permeability decreases significantly, which is basically consistent with water permeability (Figure 12(b)). However, when the effective stress increases beyond 2.5 MPa, the coal sample undergoes plastic deformation, the fracture is pressed open, and the gas permeability increases rapidly (Figure 12(b)). This shows that if the coal samples were undrained, with the increase of effective stress, the decrease of water permeability is significantly smaller than that of gas permeability (Figure 12). The coal seam water efficiently alleviates the effect of the effective stress, and plays a significant role in propping up of pores and fractures in coal. Furthermore, it is further confirming that the control of the effective stress on permeability is concentrated in the initial stage of coal seam pressure reduction. In gas production stage, the effect of effective stress on permeability is greatly reduced due to the low coal seam pressure reduction, and the propping of fractures by water further reduces the effect of effective stress. Therefore, the matrix shrinkage is the main contributing factor for permeability enhancement.

While producing CBM in No.3 coal seam, initially the coal seam pressure near wellbore reduced, the process may cause a decline in coal seam permeability. However, with the desorption of methane, the effect of coal matrix shrinkage gains strength, causing the coal seam permeability to increase in an area of 100 m around the wellbore. With incremental production of CBM well, the pressure reduction in the coal seam gradually spreads outward, and the coal seam permeability in the area beyond 100 m from the wellbore may also have a small increment. Due to the dense well pattern of No.3 coal seam, its pressure drop is relatively balanced, and gas desorption has taken place in a relatively large area of the coal seam, which alleviates the effect of effective stress. No.15 coal seam has relatively strong water content and relatively stable water supply, which further alleviates the effect of effective stress. That’s why the effective stress is weak in No.3 and No.15 coal seam, and determined that there is no large decrease of coal seam permeability during CBM well production, which ensures the feasibility of increased CBM output with increasing drainage rate.

**Conclusion**

In this study, a multi-field fully coupled mathematical model for CBM production was established to analyze the multilayer drainage of CBM well group in southern Qinshui basin under different drainage rates. Based on the numerical simulation results, the characteristic of CBM well production and key factors influencing the CBM production were further discussed. The main conclusions are as follows.

1. Increasing the drainage rate appropriately can increase the gas production of CBM wells and CBM recovery of coal seam. The exploration potential of CBM in No.3 coal seam is relatively low due to the small residual CBM content and insignificant pressure drop potential caused by the long production time. Therefore, it is recommended to improve the gas production and CBM recovery in No.15 coal seam. The average hydraulic pressure drop should be 0.018-0.031 MPa/day, which can not only induce large gas production, but also avoid the effective stress and velocity sensitivity effect.

2. The coal seam pressure influences the gas production of CBM wells through superimposed well interference. The superimposed well interference of No.3 coal seam is so well
developed that pressure drop potential is insignificant. Increasing the drainage rate can significantly improve the pressure drop and superimposed well interference of No.15 coal seam, which can promote CBM well gas production. Therefore, increasing the number and density of well in No.15 coal seam is an effective way to improve the daily gas production of CBM wells. The CBM content in coal seam is the prerequisite for CBM well production. After a long period of production, the CBM content in No.3 coal seam has reduced to a low level, which is an important reason for the insignificant increase of CBM production under 2 to 7 times drainage rate. No. 15 coal seam has larger residual CBM content, which has greater exploring potential. The coal seam permeability is mainly affected by the shrinkage effect of coal matrix produced by CBM desorption and the effect of effective stress. The effective stress is weak in No.3 and No.15 coal seam, and the main effect on the coal seam permeability is due to the shrinkage of coal matrix, which ensures that an increase in gas production of CBM wells by increasing drainage rate is feasible.

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