Mathematical model of methane driven by hydraulic fracturing in gassy coal seams

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Abstract
During hydraulic fracturing in gassy coal, methane is driven by hydraulic fracturing. However, its mathematical model has not been established yet. Based on the theory of ‘dual-porosity and dual-permeability’ fluid seepage, a mathematical model is established, with the cleat structure, main hydraulic fracture and methane driven by hydraulic fracturing considered simultaneously. With the help of the COMSOL Multiphysics software, the numerical solution of the mathematical model is obtained. In addition, the space–time rules of water and methane saturation, pore pressure and its gradient are obtained. It is concluded that (1) along the direction of the methane driven by hydraulic fracturing, the pore pressure at the cleat demonstrates a trend of first decreasing and later increasing. The pore pressure gradient exhibits certain regional characteristics along the direction of the methane driven by hydraulic fracturing. (2) Along the direction of the methane driven by hydraulic fracturing, the water saturation exhibits a decreasing trend; however, near the cleat or hydraulic fracture, the water saturation first increases and later decreases. The water saturation in the central region of the coal matrix block is smaller than that of its surrounding region, while the saturation of water in the entire matrix block is greater than that in the cleat or hydraulic fracture surrounding the matrix block. The water saturation at the same space point increases gradually with the time progression. The space–time distribution rules of methane saturation are contrary to those of the water saturation. (3) The free methane driven by hydraulic fracturing includes the original free methane and the free methane desorbed

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from the adsorption methane. The reduction rate of the adsorption methane is larger than that of free methane.

**Keywords**
Effect of methane driven by hydraulic fracturing, water saturation, methane saturation, pore pressure, pore pressure gradient

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**Introduction**

During the process of hydraulic fracturing in gassy coal, the methane concentration of the airflow in the roadway increases considerably (Huang and Lu, 2018; Lu et al., 2019). This phenomenon is known as the effect of methane driven by hydraulic fracturing. The existence of this phenomenon has been demonstrated in laboratory experiments, and the effect has both advantages and disadvantages in production practice (Chen, 2015; Huang et al., 2013, 2016). Although the effect can provide novel approaches and technologies for the exploitation of coalbed gas and hydraulic measures used to eliminate methane outbursts, it can increase the methane concentration of the airflow in the roadway in addition to the methane content and methane pressure of the local region in the coal seam, which is detrimental to the prevention of coal and methane outbursts and methane explosions (Cheng, 2012; Huang et al., 2016). However, the mathematical model of methane driven by hydraulic fracturing, considering the effect of methane adsorption and desorption, has not been established yet. Furthermore, the tendencies of water and methane saturation, pore pressure and its gradient are yet unknown. Owing to the abovementioned reasons, it is desirable to establish a mathematical model of methane driven by hydraulic fracturing.

A coal seam is characterized by the complex and variable structure of the pore and fracture, which directly determines the transport mode of the fluid (methane, water, etc.) in the coal seam. At present, the two-phase seepage model of water and gas in the coal seam with double porosity is divided into the double porosity and single seepage model and the double porosity and dual seepage model. Darcy’s law is used to describe the process of fracturing fluid flow in the abovementioned two models (Hosking et al., 2018; Thararoop et al., 2012; Yun et al., 2018; Zhang, 2014; Zhang and Bian, 2015; Zhang et al., 2016; Zou et al., 2015). Only the fracture permeability is considered in the double porosity and single permeability model, while both the fracture and pore permeability are considered in the double porosity and dual permeability model. In other words, only one permeability exists in the double porosity and single permeability model; however, two different permeabilities exist in the double porosity and double permeability model (King et al., 1986; Remner et al., 1984a, 1984b). Most natural fractures in the coal seam are in a closed state, which has negligible effect on the permeability improvement of the coal seam. The connectivity of the pores in a coal seam, which is increased by the hydraulic fractures, is significantly different from that pertaining to the natural fractures (Chong et al., 2017; Jamison and Azad, 2017; Preisig et al., 2015). At present, the permeability of these two types of fractures has not been distinguished clearly in the mathematical models of water–methane two-phase seepage flow in dual–medium coal seams. A study on the mathematical model and rules, in which the
permeability difference of the above two types of fractures is considered for the methane driven by hydraulic fracturing, has not been conducted yet.

Based on the theory of ‘dual-porosity and dual-permeability’ fluid seepage in a dual-porosity coal seam, the conceptual and mathematical model of methane driven by hydraulic fracturing is established, with the cleat structure of the coal seam, main hydraulic fracture and methane-driven process by hydraulic fracturing considered simultaneously. With the help of the COMSOL Multiphysics software, the numerical solution of the mathematical model is obtained. In addition, the space–time rules of water and methane saturation, pore pressure and its gradient are obtained.

**Conceptual model of the methane driven by hydraulic fracturing**

Pores and fractures exist in a coal seam, which make the coal reservoir capable of gas storage and allow the coalbed methane to participate in the diffusion-seepage-migration process. The pores are the main storage place of coal seam methane, and their structural characteristics have a significant effect on the accumulation and diffusion migration of the coal seam methane. Fractures are the main channels of methane migration; they are related to the permeability of the reservoir and determine the yield of the coal seam methane. The natural fractures in the coal seam are also known as cleats (Figure 1). The continuous cleats in the coal seam are called face cleats, and the discontinuous cleats, which end at the surface cleat or intersect with a face cleat, are called butt cleats. These two cleats are usually perpendicular or nearly orthogonal to each other.

Both free and adsorbed methane are present in the coal seam, and they occur in an equilibrium state. With the change in the coal seam pressure, the adsorbed and free methane move and perform exchange between each other constantly. To fully utilize the methane released from the coal seam, it is necessary to ensure that the adsorbed methane is constantly changed into free methane. In other words, the essence of the methane output is a process of continuous release of free methane. Under the action of high-pressure water, hydraulic fractures are generated in the coal seam. In the context of natural fractures, hydraulic fractures can be considered artificial fractures. The main hydraulic fractures usually extend along the direction of the maximum principal stress. When high-pressure water penetrates the natural fractures, artificial fractures and matrix pores, it drives the free methane in the natural fractures, artificial fractures and matrix pores into free space. Based on

![Diagram of the coal seam texture.](figure1.png)
the structural characteristics of the coal seam, the shape of the main hydraulic fracture and
the process of methane driven by hydraulic fracturing, the conceptual model of the methane
driven by hydraulic fracturing can be established, as shown in Figure 2.

**Mathematical model of the methane driven by hydraulic fracturing**

**Basic assumptions**

The basic assumptions for the mathematical model are as follows:

1. The solubility of the coal seam methane in water is ignored, and thus the process of
   methane driven by hydraulic fracturing is a water–gas two-phase flow in the coal seam.
2. The temperature of the seepage field is constant. A state of thermal balance exists among
   the water, methane and coal rock, and no heat transfer occurs among them. The flow of
   fluid in the artificial fractures, natural fractures and matrix pores pertains to laminar
   migration, which obeys Darcy’s law.
3. The solid skeleton and pores of the coal rock are compressible.
4. The porous medium of the coal is elastic and its deformation is small. The capillary
   pressure and gravity are considered.
5. Coal seam methane is an ideal gas, and the effect of methane adsorption occurs only in
   the matrix pores.
6. The coal seam is a double medium with pores and fractures, which are characterized by
   independent porosity and permeability.

**Governing equations**

1. Governing equations of stress

   Based on the elastic theory of porous media, the constitutive equation, which considers the
effect of methane adsorption and desorption, is as follows (Li et al., 2016; Liu et al., 2016).

   \[
   \varepsilon_{ij} = \frac{1}{2G} \sigma_{ij} - \left( \frac{1}{6G} - \frac{1}{9K} \right) \sigma_{kk} \delta_{ij} + \frac{\alpha_m}{3K} p_m \delta_{ij} + \frac{\alpha_f}{3K} p_f \delta_{ij} + \frac{\varepsilon_a}{3} \delta_{ij} \]

   \[
   (1)
   \]
where

\[
\begin{align*}
i, j, k &= 1, 2, 3 \\
G &= E / [2(1 + \nu)] \\
E &= 1 / [1/E_s + 1/(ak_n)] \\
K &= 2G(1 + \nu)/3(1 - 2\nu) = E/3(1 - 2\nu) \\
\alpha_m &= 1 - K/K_s \\
\alpha_f &= 1 - K/(aK_n) \\
\varepsilon_s &= \beta_{sg} V_{sg} = \beta_{sg} V_{Lp_m} \frac{P_m + P_L}{p_m + P_L}
\end{align*}
\]

where \(G\) is the shear modulus; \(E\) is the elastic modulus; \(\nu\) is Poisson's ratio; \(K_s\) is the volume of the coal skeleton; \(E_s\) is the elastic modulus of the coal skeleton; \(a\) is the width of the coal matrix block; \(K_n\) is the stiffness of the fractures; \(\sigma_{ij}\) is the component of stress; \(p_m\) is the pore pressure; \(p_f\) is the fluid pressure in the fracture; \(\alpha_m(\leq 1)\) is the Biot-effective stress coefficient corresponding to the pores; \(\alpha_f(\leq 1)\) is the Biot-effective stress coefficient corresponding to the fractures; \(K\) is the volume modulus of coal; \(\delta_{ij}\) is the Kronecker symbol (when \(i = j\), \(\delta_{ij} = 1\); when \(i \neq j\), \(\delta_{ij} = 0\)); \(\varepsilon_s\) is the adsorption strain of methane; \(\beta_{sg}\) is the adsorption strain coefficient of the coalbed methane; \(V_{sg}\) is the content of the adsorbed methane; \(P_L\) is the Langmuir pressure constant and \(V_L\) is the Langmuir volume constant.

According to the theory of elasticity, the relation between strain and displacement is as follows

\[
\varepsilon_{ij} = \frac{1}{2} (u_{ij} + u_{ji})
\]

It can be obtained from the static equilibrium condition that

\[
\sigma_{i,j,j} + F_i = 0
\]

Substituting equations (1), (2) and (3) into equation (4), and the modified Navier balance equation (5) with the displacement as the fundamentally unknown quantity, the coupling term included can be obtained.

\[
Gu_{i,j,j} + (G + \lambda)u_{i,j,j} - \alpha_m p_{m, i} - \alpha_f p_{f, i} - K\varepsilon_{s,j,i} + F_i = 0
\]

where \(u_i\) is the displacement along the \(i\) direction; and \(F_i\) is the volume force along the \(i\) direction \((i = x, y, z)\).

2. Mass conservation equations

The hydraulic fractures are denoted by subscript ‘f’, and the natural fractures are denoted by subscript ‘f1’. The matrix micro-fractures or pores are denoted by subscript ‘m’, and the matrix is denoted by subscript ‘M’.
Mass conservation equations of water and methane in the hydraulic fractures

The mass conservation equation of water in the hydraulic fractures is as follows

\[
\nabla \cdot \left[ \frac{\rho_g K_f K_{rg}}{\mu_g} (\nabla p_{fg} - \rho_g g \nabla D) \right] + Q_{mf} + Q_{ff} + Q_g = \frac{\partial}{\partial t} (\phi_f \rho_g S_{fg}) \quad (6)
\]

The mass conservation equation of methane in the hydraulic fractures is as follows

\[
\nabla \cdot \left[ \frac{\rho_w K_f K_{rw}}{\mu_w} (\nabla p_{fw} - \rho_w g \nabla D) \right] - \frac{k_m k_{rw} \rho_w}{\mu_w} (p_{fw} - \rho_{fw} g \nabla D) + Q_w = \frac{\partial}{\partial t} (\phi_f \rho_w S_{fw}) \quad (7)
\]

Mass conservation equations of water and methane in the natural fractures

The mass conservation equation of water in the natural fracture is as follows

\[
\nabla \cdot \left[ \frac{\rho_g K_{f1} K_{rg}}{\mu_g} (\nabla p_{f1g} - \rho_g g \nabla D) \right] + Q_{m1} + Q_{mf1} - Q_{f1} = \frac{\partial}{\partial t} (\phi_{f1} \rho_g S_{f1g}) \quad (8)
\]

The mass conservation equation of methane in the natural fracture is as follows

\[
\nabla \cdot \left[ \frac{\rho_w K_{f1} K_{rw}}{\mu_w} (\nabla p_{f1w} - \rho_w g \nabla D) \right] + \frac{k_{f1w} k_{rw} \rho_w}{\mu_w} (p_{f1w} - \rho_{f1w} g \nabla D) - \frac{k_{m1w} k_{rw} \rho_w}{\mu_w} (p_{f1w} - \rho_{f1w} g \nabla D) = \frac{\partial}{\partial t} (\phi_{f1} \rho_w S_{f1w}) \quad (9)
\]

Mass conservation equations of water and methane in the matrix

The mass conservation equations of methane in the matrix are as follows

\[
\nabla \cdot \left[ \frac{\rho_g K_m K_{rg}}{\mu_g} (\nabla p_{mg} - \rho_g g \nabla D) \right] + Q_{mM} + Q_{mf1} = \frac{\partial}{\partial t} \left[ \phi_m \rho_g s_{mg} + (1 - \phi_f - \phi_{f1} - \phi_m) \frac{V_L \rho_{mg}}{p_L + p_{mg}} \right] \quad (10)
\]
The mass conservation equations of water in the matrix are as follows

\[
\nabla \cdot \left[ \rho_w K_m K_{rw} \left( \nabla p_{mw} - \rho_w \frac{\nabla D}{\mu_w} \right) \right] + \frac{K_m K_{rw} \rho_w}{\mu_w} (p_{fw} - p_{mw}) \\
+ \frac{K_m K_{rw} \rho_w}{\mu_w} (p_{f1w} - p_{mw}) = \frac{\partial}{\partial t} \left( \phi_m \rho_w S_{mw} \right)
\]

(11)

4. Exchange quantity of methane between matrix system and fracture system

The methane diffuses into the fracture system from the coal matrix. The formula for calculating the methane exchange quantity between the matrix and fracture system is as follows (Feng et al., 2015; Li et al., 2016)

\[
-Q_{Mf} - Q_{Mf1} - Q_{Mm} = \delta_f \frac{\rho_g K_m K_{rg}}{\mu_g} (p_{mg} - p_{fg})
\]

(12)

\[
\frac{K_m K_{rw} \rho_w}{\mu_w} (p_{fw} - p_{mw}) + \frac{K_m K_{rw} \rho_w}{\mu_w} (p_{f1w} - p_{mw}) = \delta_f \frac{\rho_w K_m K_{rg}}{\mu_w} (p_{fw} - p_{Mw})
\]

(13)

where \(Q_g\) is the exchange quantity of the methane diffusing from the matrix system to the fracture system; \(\delta\) is the fracture shape factor of the matrix block, and \(\delta = \pi^2 \left[ \left( \frac{1}{L_x^2} \right) + \left( \frac{1}{L_y^2} \right) + \left( \frac{1}{L_z^2} \right) \right] \) \(L_x, L_y, \) and \(L_z\) are the intervals of fractures along the \(x, y,\) and \(z\) directions, respectively.

3. Relationship equation of capillary pressure with the pressure and saturation in the fracture and matrix

The expression of capillary pressure in the hydraulic fractures is as follows

\[
p_{fc} = p_{f1w} - p_{fw} = p_{fc}(S_{efw})
\]

(14)

The expression of capillary pressure in the natural fractures is as follows

\[
p_{f1c} = p_{f1nw} - p_{f1w} = p_{f1c}(S_{ef1w})
\]

(15)

The expression of capillary pressure in the matrix pores is as follows

\[
p_{cm} = p_{mnw} - p_{mw} = p_{cm}(S_{emw})
\]

(16)

The pores and fractures are always filled with fluid. The water and methane two-phase saturation in the hydraulic fracture is expressed as follows
The expression of water and methane saturation in the natural fracture is as follows

\[ S_{f_{1g}} + S_{f_{1w}} = 1 \]  

(17)

The water and methane two-phase saturation in the matrix pores can be expressed as follows

\[ S_{mg} + S_{mw} = 1 \]  

(19)

4. Porosity and absolute permeability of coal matrix and fracture

The porosity of the coal matrix and fracture can be respectively expressed as follows (Fan et al., 2016; Liu et al., 2017; Zhang et al., 2017).

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

(20)

\[
\phi_f = \phi_{f0} - \frac{3\phi_{f0}(\Delta \varepsilon_s - \Delta \varepsilon_v)}{\phi_{f0} + 3K_f/K} 
\]  

(21)

where \( \phi_m \) is the porosity of the coal matrix; \( S = \varepsilon_v + p_m/K_s - \varepsilon_s; \) \( S_0 = \varepsilon_{v0} + p_{m0}/K_s - \varepsilon_{s0}; \) \( K_s \) is the volume modulus of the coal skeleton; \( z_m \) is the Biot-effective stress coefficient corresponding to the pore; \( \phi_f \) is the porosity of the fracture; \( \varepsilon_s \) is the skeleton strain caused by the adsorbed methane; \( \varepsilon_v \) is the volume strain of coal, and \( \varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z; \) \( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are the respective volume strains along the directions of \( x, y \) and \( z; \) \( K_f \) is the improved stiffness of the fracture, and \( K_f = bK_m; \) \( b \) is the width of the fracture and subscript ‘0’ represents the initial value.

A cubic relationship exists between the absolute permeability of the matrix and fracture and their porosity, and the corresponding expressions are as follows (Li et al., 2016; Palmer, 2009; Zhang, 2016).

\[
\frac{k_m}{k_{m0}} = \left( \frac{\phi_m}{\phi_{m0}} \right)^3 \left( \frac{1 - \phi_{m0}}{1 - \phi_m} \right)^2 
\]  

(22)

\[
\frac{k_f}{k_{f0}} = \left( \frac{\phi_f}{\phi_{f0}} \right)^3 = \left( 1 - \frac{3(\Delta \varepsilon_s - \Delta \varepsilon_v)}{\phi_{f0} + 3K_f/K} \right)^3 
\]  

(23)

5. Relative permeability of water and methane

Based on the Brooks and Corey-Burdine (BCB) model, a new relative permeability model of water and methane, applicable to a coal reservoir with joints, was deduced by Chen Dong et al. The expression of the new model is as follows (Chen et al., 2013; Corey and Rathjens, 1956).
where $\lambda$ is the index representing the scale distribution of coal joints; and $\eta$ is the index representing the bend degree of coal joints.

The physical meaning of the parameters $\lambda$ and $\eta$ in equations (24) and (25) can be illustrated by Figure 3. Research has demonstrated that the parameters $\lambda$ and $\eta$ considerably influence the results of the numerical simulation; the range of parameter $\eta$ is between 0 and 2, and the range of parameter $\lambda$ is between 0.3 and 8.8 (Chen et al., 2013; Bertrand et al., 2017).

**Boundary conditions**

Water enters into the interior of the coal body along the hydraulic fractures or cleats, and it causes the seepage of methane forward in the coal seam. The mathematical form of the boundary and initial conditions of the physical model is as follows

\[
p_{w} = p_{w}(t) \quad \partial \Omega \text{ Borehole boundary} \tag{26}
\]

\[
p_{g} = p_{g0} \quad \partial \Omega \quad \text{Outlet boundary} \tag{27}
\]

\[
n \cdot \rho_{w} [-\lambda_{w}(\nabla p_{w} + \rho_{w}g\nabla D)] = 0 \quad \partial \Omega \quad \text{Bottom and top boundaries} \tag{28}
\]

\[
n \cdot \rho_{g} [-\lambda_{g}(\nabla p_{g} + \rho_{g}g\nabla D)] = 0 \quad \partial \Omega \quad \text{Bottom and top boundaries} \tag{29}
\]

\[
p = p_{0} \quad \partial \Omega \tag{30}
\]

**Numerical simulation of the methane driven by hydraulic fracturing**

**Geometric models**

The geometric model (Figure 4) of the coal seam used in this study has a length of 20 m and width of 6 m. The blue circle represents the fracturing borehole, whose diameter is 0.075 m. The natural fractures and the main hydraulic fractures are represented by the black and magenta lines, respectively. The roof of the coal seam, which bears the overburden gravity, is simulated by the upper boundary of the geometric model. The floor of the coal seam is simulated by the lower boundary of the geometric model, which is a fixed boundary. Neither water nor methane can penetrate the upper and lower boundaries. Both the right and left boundaries of the geometric model are sliding and permeable boundaries. The maximum principal stress is along the vertical direction, and the minimum principal stress direction is along the horizontal direction.
**Parameter selection**

To make the process of numerical simulation as factually accurate as possible, real physical parameters are used in the numerical simulation. The relevant parameters used in this numerical simulation are listed in Table 1.

**Analysis of numerical simulation results**

*Space–time distribution rules of pore pressure.* The space distribution of the pore pressure at the times 0.1 h, 0.5 h, 1.0 h and 1.5 h is shown in Figure 5. It can be seen from Figure 5 that the (1) methane pressure at the boundary of the coal seam is lower than that inside the coal seam. This finding can be explained by the fact that the methane flows into the cleat or hydraulic fracture from the matrix block and migrates around the coal seam under the driving action of the high-pressure water. The free methane in the coal seam flows through the permeable boundary to the free space around the coal seam, resulting in the methane pressure at the boundary of the coal seam being lower than that inside the coal seam. (2) At a central time, the pore pressure in a matrix block is considerably higher than that in the adjacent cleat or hydraulic fracture. This phenomenon is due to the occurrence of the coal seam methane in the matrix block. (3) The methane pressure inside the hydraulic fracture and cleat connected to the hydraulic fracture is significantly higher than that in other parts.
Table 1. Parameters used in the numerical simulation.

| Symbol | Physical parameter | Value | Unit |
|--------|---------------------|-------|------|
| \( \rho_w \) | Density of water | 1000 | kg/m³ |
| \( \rho_g \) | Density of methane under standard condition | 0.716 | kg/m³ |
| \( E \) | Elastic modulus of coal | 2713 | MPa |
| \( E_s \) | Elastic modulus of coal skeleton | 8469 | MPa |
| \( \mu \) | Poisson’s ratio | 0.32 | - |
| \( \mu_0 \) | Initial porosity of matrix | 0.04 | - |
| \( S_r \) | Stiffness of fracture | 4800 | MPa/m |
| \( S_{r,w} \) | Dynamic viscosity of water | 1.84 | Pa·s |
| \( S_{r,g} \) | Saturation of residual methane | 0.1 | - |
| \( \rho_{g,0} \) | Initial porosity of fracture | 0.08 | - |
| \( \rho_s \) | Density of coal skeleton | 1470 | kg/m³ |
| \( k_r \) | Relative permeability of methane at endpoint | 11 | - |
| \( K_m \) | Permeability of matrix | 1e-18 | m² |
| \( k_{r,0} \) | Permeability of matrix at initial equilibrium | 6 | MPa |
| \( \sigma_1 \) | Minimum principle stress | 6 | MPa |
| \( \sigma_3 \) | Maximum principle stress | 1e-18 | MPa |
| \( b \) | Langmuir limiting methane adsorption constant | 3.304 | MPa⁻¹ |
| \( \alpha \) | Langmuir limiting methane adsorption constant | 0.036 | m³/kg |
| \( \beta \) | Initial pore pressure | 10 | MPa |
| \( \delta \) | Langmuir limiting methane adsorption constant | 3.304 | - |
| \( \gamma \) | Langmuir limiting methane adsorption constant | 3.304 | - |

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This aspect can be explained by the fact that the high-pressure water, which flows into the coal matrix through hydraulic fractures, has an effect of compression on the free methane in the coal matrix, resulting in the methane pressure of the internal coal matrix being higher than that within its surrounding area.

It can be seen from Figure 6 that (1) when the time is fixed, the pore pressure of the coal seam is continuously distributed along the direction of the methane driven by water. The initial pore pressure of the coal seam is 1.2 MPa, while the range of the pore pressure during the process of methane driven by water is 0.1–2.0 MPa. Among these values, the pore pressure near the borehole is higher than the initial pore pressure, while the pore pressure near the boundary of the coal seam is lower than the initial pore pressure. It is indicated that after the high-pressure water enters the coal seam, the pore pressure in the coal seam is redistributed, resulting in the appearance of zones involving an increase and decrease in the pore pressure. (2) When the time is fixed, the pore methane pressure in the same matrix block presents low values at both the ends and high values in the middle of the matrix block.
along the direction of the methane driven by water. The reason is that the methane in the matrix block flows from the centre of the matrix to the cleat or hydraulic fracture inside both the sides. The methane pressure in the middle of the matrix block is the highest, while the methane pressure at both ends of the same matrix block is relatively low. (3) When the time is fixed, along the direction of the methane driven by water, the pore pressure presents a notable abrupt change at the cleat. This phenomenon can be explained by the fact that the methane pressure in the cleat is lower than that in its adjacent upstream and downstream matrix blocks. (4) The pore pressure, in a certain range of the fracturing borehole, increases with time progression, while the pore pressure outside this range decreases with time progression.

**Space–time distribution rules of pore pressure gradient.** The pore pressure gradient on the monitoring line at times 0.1 h, 0.5 h, 1 h and 1.5 h is shown in Figure 7. The pore pressure gradients near the borehole, at the cleat or fracture and the boundary of the coal seam change significantly (Figure 7(a)). This phenomenon can be attributed to the regional characteristics of the pore pressure gradient in the direction of the methane driven by hydraulic fracturing.

Figure 7(b) shows that (1) when the time is fixed, the pore pressure gradient of the space point near the fracturing borehole gradually decreases along the direction of the methane driven by hydraulic fracturing. This phenomenon occurs because inside the coal matrix close to the fracturing borehole, a larger distance from the fracturing borehole corresponds to a weaker degree of methane compression; in addition, a lower methane pressure corresponds to a smaller methane pressure difference between two adjacent space points. (2) When the location of the space point is certain, the pore pressure gradient at the spatial point gradually increases with time progression. This finding is explained by the fact that with the continuous process of methane driven by hydraulic fracturing, the methane pressure on the
space point increases under the influence of the water pressure, resulting in the increase in the methane pressure difference between the space point and its adjacent space point.

It can be seen from Figures 7(c), 7(d) and 7(e) that (1) when the time is fixed, the pore pressure gradient at the space point in the cleat or fracture is considerably lower than that

Figure 7. Curves of pore pressure gradient along the horizontal monitoring line.
inside its adjacent matrix block. This pore pressure gradient difference becomes the driving force of the methane flowing from the matrix block to the cleat or fracture. (2) When the position of the space point is fixed, the pore pressure gradient at this point decreases with time progression. The reason is that the free methane at this point constantly flows into the cleat or fracture of the coal seam, and the methane content in the coal matrix decreases as well. As a result, the methane pressure in the coal matrix decreases, eventually resulting in a decrease in the pore pressure gradient with time progression.

It can be seen from Figure 7(f) that (1) at times 0.1 h, 0.5 h, 1.0 h and 1.5 h, the corresponding pore pressure gradients on the 0.1 m space distance increase by 4.765 MPa/m, 4.311 MPa/m, 3.652 MPa/m and 3.264 MPa/m. This aspect indicates that when the time is fixed, the pore pressure gradient near the boundary of the coal seam exhibits a notable trend of increase along the direction of the methane driven by the hydraulic fracturing. (2) At times 0.1 h, 0.5 h, 1.0 h and 1.5 h, the pore pressure gradients at the 10 m space point are 5.814 MPa/m, 5.392 MPa/m, 4.741 MPa/m and 4.335 MPa/m, respectively. This aspect indicates that when the space point near the boundary of the coal seam is fixed, the pore pressure gradient at this point decreases with time progression.

Space–time distribution rules of water and methane saturation during the process of methane driven by hydraulic fracturing

(1) Visualization of space–time distribution of water-methane two-phase saturation. The space–time distributions of water and methane saturation at times 0.1 h, 0.5 h, 1.0 h and 1.5 h are shown in Figure 8. It can be observed from Figure 8(a) that (1) the borehole is located inside the matrix block, and the water saturation in the matrix block around the borehole is increasing. This finding is apparently a result of the continuous flow of water into the interior of the coal matrix. (2) Inside the coal matrix block, the water saturation in its central region is lower than the water saturation in its surrounding region. This finding occurs because when water penetrates the matrix block through cleats or hydraulic fractures, the water first infiltrates the surrounding matrix block and later flows into its central matrix block gradually. (3) The water saturation in the entire matrix block is larger than that in its surrounding fracture or cleat. The reason is that after water enters the inner part of the matrix block, the methane inside the matrix block is driven into the cleat or fracture surrounding the matrix block. As a result, the space occupied by water in the matrix space is greater than that in the cleat or fracture. Because the sum of the water and methane saturation is always 1, the space–time distribution rules of methane saturation (Figure 8(b)) are opposite to those of water saturation.

(2) Space–time distribution of water and methane saturation. The space–time distribution of water saturation on the monitoring line at times 0.1 h, 0.5 h, 1.0 h and 1.5 h is shown in Figure 9. It can be seen from Figure 9(a) that (1) when the time is constant, the water saturation demonstrates a decreasing trend along the direction of methane driven by hydraulic fracturing. This phenomenon occurs because when water is continuously injected into the coal seam from the fracturing borehole, the water flows from the closest point to a distant point, and the fracturing borehole is in the centre of these points. The closer it is to the fracturing borehole, the more space water occupies. The outward performance is that the water saturation gradually decreases along the direction of the methane driven by hydraulic fracturing in space. (2) When the time is fixed, the water saturation demonstrates a trend of first increasing and later decreasing near the cleat or hydraulic fracture along the direction of
methane driven by hydraulic fracturing. This aspect indicates that when the space position transits from the upstream matrix block to the adjacent downstream matrix block through the cleat or hydraulic fracturing, the water saturation first increases and later decreases. The reason is that the water saturation of the upstream and downstream matrix blocks is

Figure 8. Space–time distribution of water and methane saturation.
Figure 9. Space–time distribution curve of water and methane saturation.
different from that of the cleat or fracture along the direction of the methane driven by hydraulic fracturing. (3) To a certain position, water saturation gradually increases with time progression. This phenomenon is explained by the fact that with time progression, the amount of water flowing through the point increases, resulting in an increase in the water saturation at the space point. Similarly, because the sum of the methane and water saturation is always 1, the space–time distribution rules of methane saturation (Figure 9(b)) are contrary to those of water saturation.

Variation of methane content in coal seam over time with methane driven by hydraulic fracturing. In the process of methane driven by hydraulic fracturing, the curve of the total methane content, adsorbed methane content and free methane content of the coal seam over time is shown in Figure 10. It can be seen from Figure 10 that the free methane content, adsorbed methane content and total methane content decrease with the time progression, and the reduction rate of the adsorbed methane content is higher than that of the free methane content. This phenomenon occurs because during the process of methane driven by hydraulic fracturing, the free methane in the coal seam is first driven out by water. Subsequently, the dynamic equilibrium state of the free and adsorbed methane in the coal seam is disrupted, resulting in the adsorbed methane transforming into free methane. In addition, the hydraulic fracturing reduces the methane pressure in some areas of the coal seam, resulting in the transformation of the adsorbed methane into free methane, which is also driven out by the high-pressure water. The decrease in the free and adsorption methane finally leads to the decrease in the total methane content in the coal seam.

Conclusions

1. During the process of methane driven by hydraulic fracturing, the pore pressure is redistributed. The methane pressure near the fracturing hole is higher than the original
methane pressure; however, the methane pressure at the boundary of the coal seam is lower than the original methane pressure. The methane pressure in the hydraulic fracture and the cleat connected with it is higher than that in their surrounding area. The pore pressure exhibits low values at both ends and high values in the middle of the same matrix block along the direction of methane driven by hydraulic fracturing; furthermore, a notable abrupt change appears at the cleat. The pore pressure at the same space point near the fracturing borehole increases with time; however, the pore pressure at the same spatial point outside the range decreases with time progression.

2. Along the direction of methane driven by hydraulic fracturing, the pore pressure gradient in the coal seam exhibits a certain regional characteristic. The pore pressure gradient near the fracturing borehole demonstrates a notable decreasing trend along the direction of methane driven by hydraulic fracturing. The pore pressure gradient at the spatial point of the cleat is significantly lower than that in its adjacent matrix blocks. However, the pore pressure gradient near the boundary of the coal seam exhibits an obvious increasing trend. The pore pressure gradient at the same space point near the fracturing borehole and the boundary of the coal seam decreases with the time progression.

3. With the help of the COMSOL Multiphysics software, the space–time distribution of water and methane saturation in the coal seam matrix and cleat or fracture can be observed directly, and the visualization of the process of methane driven by hydraulic fracturing can be realized. From the cloud map of the water and methane saturation distribution, it can be noted that along the direction of the methane driven by hydraulic fracturing, the water saturation in the coal seam exhibits an overall decreasing trend; however, it first increases and later decreases near the cleat or hydraulic fracture. The water saturation at the inner space point of the coal seam increases gradually with the time progression. Inside the matrix block, the water saturation in the central region is less than that in the surrounding region, and the water saturation in the entire matrix block is greater than that in the cleat or hydraulic fracture surrounding the matrix block. The space–time distribution rules of methane saturation are contrary to those of water saturation.

The free methane driven by the hydraulic fracturing includes the original free methane and the free methane desorbed from the adsorbed methane. The reduction rate of the adsorbed methane is larger than that of the free methane.

Data Availability
The data in the manuscript can be available on request through Weiyong Lu, whose email address is 489698551@qq.com.

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