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Research on gas transportation law in coalbed methane under different coal seam states

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Abstract: *With the development of coal mining industry, coal mine safety accidents and on-site safety management are more and more concerned. Firstly, we introduce the CBM transportation model of multi-seam system, based on Fick's law of diffusion and Darcy's law of permeability, and put forward a three-dimensional CBM transportation model with additional overflow state, which covers diffusion, seepage and overflow, and provides theoretical support for solving the problems of coal mine engineering, and points out that the model has not considered the influence of environmental factors such as electric field, temperature, and so on. Then, the source and outflow of gas from close double-seam mining are analyzed, including the calculation methods of gas outflow from the mined seam and the neighboring seams, and the gas outflow from the working face is obtained by adding the two together. It also introduces the rules of coalbed methane transportation and enrichment in mines with depleted coal resources, divides the types of residual coal and residual gas, and explores the transportation and enrichment of near horizontal coal seam single mining airspace and tilted coal seam adjacent mining airspace, and finds that residual gas of the mines with depleted coal resources exists in the airspace and other parts of the mines, and the transportation and enrichment of which are affected by a variety of factors, and the results of residual gas transportation are improved for the treatment of coalbed mining. The results of the transportation will provide a reference for the study of coalbed methane management.*

Keywords: *Coalbed gas; Transportation patterns; Multi-seam systems; Gas outflow*

1. Introduction

In the coal mining sector, coalbed methane (CBM) plays a significant role. Composed primarily of methane, it serves dual purposes: as an energy source and a factor affecting mine safety. On the one hand, CBM is a clean energy source with immense potential; on the other hand, its accumulation underground can easily lead to gas-related accidents. Conducting systematic research on the migration characteristics and patterns of CBM under various conditions is of great significance for improving the efficiency of CBM energy development and ensuring safe production in coal mines.

2. Analysis of Coalbed Methane Migration Models in Multi-Seam Systems

Diffusion and seepage are the two fundamental modes of CBM migration within coal reservoirs. In multi-seam systems, driven by inter-seam pore pressure gradients, CBM from adjacent seams can penetrate low-permeability interlayers and migrate toward the working face, goaf, or production wells of the mining seam, where it escapes. This process gives rise to the phenomenon of CBM cross-seam flow in multi-seam systems. Based on a comprehensive analysis of diffusion, seepage, and cross-flow, a holistic CBM migration model for multi-seam systems has been developed, providing a more practical theoretical basis for solving engineering problems at coal mine sites[1].

Current research on CBM migration mechanisms, both domestically and internationally, primarily focuses on two main types: first, the diffusion behavior of CBM within the pores of the coal matrix; and second, the seepage process within the fracture system. Accordingly, the classical models describing these migration patterns mainly include Fick’s law of diffusion and Darcy’s law of seepage.

2.1 Fick’s Law of Diffusion

Fick’s law of diffusion is a fundamental theory in solid-state physics used to describe macroscopic diffusion phenomena. Establishing a two-dimensional Cartesian coordinate system with the x-axis representing the horizontal direction and the y-axis representing the vertical direction, and assuming that the diffusion process occurs along the x-axis, the diffusion flux passing through a unit cross-section in the y-direction per unit time is determined by the concentration gradient of the substance n. Fick's diffusion law comprises the first and second laws, whose mathematical expressions are shown in Equations (1).

$$\begin{gathered} \mathrm{J} = -\mathrm{D}\frac{\mathrm{d}\rho}{\mathrm{dx}} \\ \frac{\partial_n}{\partial_t} = \frac{\partial}{\partial_x}\mathrm{D}\left(\frac{\partial_n}{\partial_x}\right) \end{gathered} \tag{1}$$

In the equation: J is the diffusion flux $kg/m^2 \cdot s$; D is the diffusion coefficient (m^2/s); ρ is the mass concentration kg/m^3;

2.2 Darcy's Law of Seepage

When groundwater flows through the pores of soil, energy is lost along the flow path due to seepage resistance. To elucidate the patterns of water flow through soil, the French engineer Darcy conducted extensive experimental research in 1856 and established a relationship between energy loss and flow velocity, known as Darcy's Law, as shown in Equation (2).

$$\bar{v} = \frac{\mathrm{K}}{\mu}\frac{\partial\rho}{\partial_{\mathrm{r}}} \tag{2}$$

Where: $\bar{v}$ is the gas flow velocity m/s, K is the coal seam permeability m^2, and μ is the dynamic viscosity coefficient of the gas $Pa \cdot s$;

2.3 A Ternary Migration Model for Coalbed Methane Incorporating Cross-Flow Conditions

The theory of gas cross-flow was initially applied primarily to migration simulation studies of multi-layer hydrocarbon reservoirs. Although recent domestic and international research has mentioned the phenomenon of coalbed methane cross-flow, specialized analysis and in-depth exploration of this migration mechanism remain limited.

In a single coal reservoir, CBM primarily migrates through a coupled process of diffusion and seepage; however, in multi-coal-seam systems, cross-flow is also a key migration mechanism. CBM cross-flow is essentially an unstable flow process in which compressible gas exhibits coupled diffusion and seepage characteristics within a heterogeneous porous medium containing pores and fractures. This theory applies not only to conventional oil and gas reservoirs but also to CBM systems; gas migration following the depressurization of adjacent coal seams triggered by production in the overlying reservoir is a typical example of cross-flow.

Based on this, a three-component CBM migration model incorporating cross-flow is a comprehensive migration model that unifies and couples diffusion, seepage, and cross-flow. The model assumes that coalbed methane behaves as an ideal gas, the reservoir temperature remains constant, and gas pressure is uniformly distributed within the coal seam; the strike of the coal seam is taken as the x-direction, and the dip of the coal seam as the y-direction. Under isothermal conditions, the density of coalbed methane varies only with pressure. According to Darcy's law equation (3), the seepage velocity of coalbed methane within the i-th coal seam can be obtained.

$$\mathrm{v_i} = \frac{\mathrm{K_i}}{\mu}\cdot\frac{\mathrm{p_{(i+1)}} - \mathrm{p_i}}{\mathrm{m_i}} \tag{3}$$

In the equation, $\mathrm{K_i}$ represents the permeability of the i-th coal seam in $\mathrm{m_2}$; $\mathrm{m_i}$ represents the thickness of the i-th coal seam in; m,$\mathrm{p_{(i+1)}}$ and $\mathrm{p_i}$ represent the pressure values at the upper and lower surfaces of the i-th coal seam in MPa.

The flow of coalbed methane through coal seams obeys the law of conservation of mass:

$$\mathrm{P_i v_i dx \cdot dy} = \rho_{\mathrm{vdx \cdot dy}} \tag{4}$$

In the equation: v represents the seepage velocity of gas outflow in m/min.

Based on Equations (4) and (5), the model equation for coalbed methane outflow is:

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$$p^2 - p_i^2 = 2\mu_{vp}\Sigma\frac{m_i}{K_i} \tag{5}$$

In summary, the coalbed methane migration model for the Keduo multi-seam system is as follows:

$$\begin{cases} \partial_c/\partial_t = -\nabla(\theta_m) \\ \dfrac{d^2p}{d^2} + \dfrac{1}{dr}\dfrac{dp}{dr} = 0 \\ p^2 \Big| -p^2 = 2\mu_{vp}\Sigma\dfrac{m_i}{K_i} \end{cases} \tag{6}$$

The three-component comprehensive migration model proposed above provides a relatively comprehensive description of the migration characteristics of coalbed methane in multi-seam systems. The introduction of the cross-flow mechanism effectively improves upon traditional diffusion–seepage models, helping to reveal the migration patterns of coalbed methane in a more systematic manner, while also providing new insights and a theoretical basis for the prevention and control of mine gas hazards.

Due to the inherent complexity of fluid dynamics problems, the migration model proposed in this paper does not yet account for the influence of external environmental factors. The mechanisms by which conditions such as electric fields and temperature fields affect the migration patterns of coalbed methane require further in-depth study.

2.4 Analysis of Methane Outflow in Close-Proximity Double-Seam Mining

Coalbed methane is commonly referred to as “coal mine gas” underground. Under conditions of close-spaced multi-seam mining, the primary sources of gas outbursts can be categorized into two types: first, gas outbursts generated directly from the seam being mined; and second, gas outbursts released from adjacent seams due to mining-induced stress relief [2-3].

2.5 Methane outflow from the mined coal seam

The methane outflow from the mined coal seam—that is, the methane outflow from the working face—depends primarily on the coal seam thickness, the working face height, the distance advanced, the initial methane volume, and the residual methane volume. The calculation formula is as follows:

$$q_1 = k_1 \cdot k_2 \cdot k_3 \frac{m_0}{m_1} \cdot (X_0 - X_1) \cdot \frac{l}{L} \tag{7}$$

In the equation, q_1 represents the relative gas outburst rate for the current advance distance, m³/t; $k_1$is the gas outburst coefficient of the rock formation; k_2 is the gas outburst coefficient of falling coal; k_3 is the coefficient representing the effect of ventilation pre-drainage on gas outbursts from the exposed coal face; m_0 is the coal seam thickness, m; m_1 is the mining height, m; X_0 is the initial gas content, m³/t; X_1 is the residual gas content, m³/t; l is the current face advance length, m; L is the projected face advance length, m.

2.6 Coal Seam Gas Outflow in Adjacent Seams

Following coal seam mining, deformation and failure occur in the overlying strata, creating a zone of mining-induced fractures. Within this zone, the original permeability of the coal-rock mass changes significantly, and the coal seam is fully depressurized, releasing large amounts of gas. Driven by concentration and pressure gradients, the released gas migrates and diffuses along fracture channels, forming sources of gas outbursts. After simplifying certain influencing factors, the gas outburst volume in adjacent coal seams can be calculated using the following formula:

$$q_2 = \sum_{i=1}^{n} \frac{m_i}{m_i} k_i \cdot (X_{0i} - X_{li}) \cdot \frac{l}{L} \tag{8}$$

In the equation, q_2 represents the relative gas outflow rate of the adjacent layer at the current advance distance, in m³/t; $m_i$represents the thickness of the i-th adjacent layer, in m; m_i represents the working height of the protective layer, in m; X_{0i} represents the initial gas content of the i-th adjacent layer, in m³/t; X_{li}represents the residual gas content of the i-th adjacent layer, in m³/t; and k_i represents the gas outflow rate of the i-th adjacent layer, in %.

By calculating the gas outflow rate $q_1$of the mined coal seam and the gas outflow rate q_2 of the adjacent coal seam separately, the relative and absolute gas outflow rates of the working face can ultimately be determined[4].

3. A Study on the Migration and Accumulation Patterns of Coalbed Methane in Depleted Coal Mines

China's coal industry has a long history, and prolonged mining has resulted in a large number of resource-depleted coal mines. These mines not only contain significant residual coal reserves but also generally have high methane concentrations, harboring substantial coalbed methane resources with excellent potential for development and utilization[5]. To date, relevant research has made some progress in analyzing the occurrence characteristics of coalbed methane[6], developing resource estimation methods[7-8], delineating reserve calculation boundaries[9], and establishing evaluation systems for development potential. However, research remains relatively limited regarding the core issue of the migration and accumulation patterns of coalbed methane in abandoned mines.

Based on the theoretical framework of CBM adsorption and desorption mechanisms[10]and integrating the "three-zone" development theory widely applied in coal mining[11-12], Yin Zhi sheng systematically investigated the migration patterns of CBM after mine closure by meticulously classifying residual coal types and analyzing the distribution characteristics of residual gas.

Residual coal is the primary source of CBM in depleted mines, and the classification of residual coal types is a prerequisite for studying gas migration and accumulation patterns. Considering that CBM primarily exhibits vertical migration characteristics after mine closure, residual coal can be classified into two categories based on spatial distribution: residual coal bodies in the mined seam and residual coal bodies in adjacent seams within the mining-induced impact zone. These can be further subdivided into specific types such as coal pillar residual coal and corner residual coal.

3.1 Patterns of migration and enrichment in single-seam mining goafs in near-horizontal coal seams

In the early stages of mine closure, the vertical migration of coalbed methane within a single goaf in a near-horizontal coal seam generally proceeds as follows: methane desorbed from residual coal, driven by pressure gradients, originates from the residual coal in the current seam and the residual coal in adjacent seams affected by mining operations, and migrates toward the goaf along mining-induced fractures. Since methane is less dense than air, and assuming that mechanical ventilation is still in operation in the closed mine, desorbed gas tends to accumulate and migrate primarily toward the upper part of the goaf.

After the formation of the "three zones" above the goaf, the stress in the overlying rock decreases, and the pores and fractures within the caving zone and fracture zone develop significantly, enhancing connectivity. Initially, the gas concentration within the fracture zone is lower than that at the top of the goaf; driven by both concentration and pressure gradients, the gas continues to migrate from the goaf through the fractures in the caving zone toward the fracture zone. If the overlying strata of the fracture zone are well-sealed, with no large open faults or vertically penetrating fractures, the gas will accumulate near the top of the fracture zone, forming a high-concentration enrichment zone; conversely, the gas will migrate toward shallower depths along large faults and escape at weak points on the surface, causing ground-level gas leaks.

In closed mines with active hydrodynamic conditions, when groundwater rises but does not completely submerge the goaf, the rising water level increases the pressure in the goaf. Part of the desorbed gas dissolves in the water and migrates with the groundwater, while another portion of the desorbed gas is re-adsorbed. Furthermore, if the coal seam is a tectonic coal seam, it is difficult for the internal pore and fracture system to remain stable over the long term, which is not conducive to the migration and accumulation of coalbed methane.

3.2 Patterns of migration and enrichment in adjacent goafs of inclined coal seams

During mining operations, the mining-induced effects of adjacent goafs directly alter the migration and distribution characteristics of residual gas within previously formed goafs. Suppose there are adjacent goafs I and II, where goaf I was mined and sealed first, and the gas within it has migrated to the upper fracture zone, initially forming an accumulation zone; at this point, mining activities in goaf II will generate various disturbances.

On the one hand, the mining of Goaf II will exert a pressure-relief effect on the residual coal mass in the current coal seam and adjacent seams, promoting further desorption and migration of gas from the residual coal, while the desorption and migration of gas within Goaf I will still be primarily driven by gaseous seepage. On the other hand, whether the fracture zones and subsidence zones of the two goafs overlap will directly determine the final pattern of gas migration.

If there is no overlap, the mining of Abandoned Area II will not disrupt the gas-rich zone already formed in Area I; after Area II is sealed, two mutually independent gas-rich zones will be established. If the mining of Abandoned Area II causes the scope of overburden movement to expand, leading to extensive interconnection of the fracture zones and subsidence zones in both areas and the formation of a large number of communicating and detachment fractures, and given that the gas pressure in the shallow goaf is relatively low, then after the closure of Area II, the gas previously accumulated in the upper part of Area I will, driven by a pressure gradient, undergo secondary migration along the interconnected fractures toward Area II, ultimately converging at the top of the fracture zone in the upward-dipping direction of Area II to form a larger and higher-concentration gas-rich zone. At this point, the gas pressure between goafs I and II tends toward overall equilibrium, and this area becomes the target zone with the most optimal conditions for coalbed methane development in depleted mines[13].

A summary and analysis of Yin Zhisheng's research indicates that residual coalbed methane in depleted mines is primarily concentrated in the following four areas:

Goaf: The space created by coal mining, which serves as a major accumulation site for residual gas.

Adjacent coal-rock fracture zones: Due to changes in mining-induced stress, fractures form in adjacent rock strata, creating the primary pathways for gas migration and accumulation.

Residual coal in the original coal seam: Coal left in situ after mining, which still contains large amounts of coalbed methane.

Residual coal in adjacent seams following stress relief: Adjacent coal seams where stress has been released due to mining-induced effects, causing continuous desorption and migration of gas.

At the same time, Yin Zhisheng's research indicates that the migration and accumulation of residual gas in abandoned mines are controlled by multiple factors, primarily including:

Depth of the goaf: The greater the depth, the more difficult it is for gas to escape to the surface.

Permeability of the reservoir and surrounding rock: The higher the permeability, the more unimpeded the gas migration.

Fault structures: Faults can serve as preferential migration pathways for gas.

Hydrogeological conditions: Groundwater activity influences the migration, occurrence, and accumulation of gas.

These factors collectively determine the development potential of coalbed methane resources in abandoned mines.

Research also indicates that after mine closure, the patterns of gas migration and accumulation vary significantly among coal seams with different geological conditions:

Near-horizontal coal seams: Residual gas migrates primarily vertically upward, eventually forming high-concentration accumulation zones at the top of the fracture zone.

Inclined coal seams: Mining in shallow goafs disturbs the gas migration in deep, previously sealed goafs. If the fracture zones of adjacent goafs are not interconnected, they each form independent gas-rich zones; if the fracture zones are interconnected, gas from the deep goafs undergoes secondary migration, forming a unified accumulation zone in the upward-sloping direction of the shallow goafs.

4. Conclusion

Based on the above theoretical analysis and research findings, the following conclusions can be drawn:In multi-seam systems, coalbed methane migration involves three basic forms: diffusion, seepage, and cross-flow. Cross-flow refers to the phenomenon in which gas from adjacent coal seams migrates to the mined seam through low-permeability interlayers; it is a migration mechanism of equal importance to diffusion and seepage and cannot be ignored.

A three-component CBM transport model that accounts for cross-flow can more comprehensively characterize the gas transport patterns within multi-seam systems, providing more practical theoretical support for solving engineering problems at coal mine sites.

Under close-spaced double-seam mining conditions, gas outbursts primarily originate from the current mining seam and adjacent seams affected by mining operations. Gas outburst volume in the mining seam is controlled by factors such as seam thickness, mining height, advance distance, initial gas content, and residual gas content; gas outburst volume in adjacent seams primarily depends on parameters such as adjacent seam thickness, mining height, initial gas content, residual gas content, and gas release rate.

In depleted mines, residual gas is primarily found in goafs, fracture zones in adjacent coal and rock strata, residual coal within the current mining seam, and residual coal in adjacent seams following pressure relief. After mine closure, gas in the goaf migrates vertically from the goaf through the caving zone toward the fracture zone, forming a high-concentration accumulation zone at the top of the fracture zone. In the case of inclined coal seams, mining in shallow goafs affects the gas migration in deep, sealed goafs: if the fracture zones of adjacent goafs are not connected, they each form independent gas-rich zones; if the fracture zones are connected, gas from the deep goafs undergoes secondary migration, forming a unified gas-rich zone in the upward direction of the shallow goaf.

These research findings provide a theoretical basis and guidance for the prevention and control of coal mine gas hazards and the development of coalbed methane resources.

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