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Study on Seepage of Coalbed Methane in Pore-fracture Double - porosity Medium

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ABSTRACT

The study of coalbed methane (CBM) seepage within dual-porosity medium constitutes a significant research endeavor in the field of geology and coalbed methane reservoir engineering. This research delves into the complex dynamics governing CBM flow through porous coal matrices within dual-porosity systems. Employing advanced methodologies including numerical simulation and experimental analysis, this investigation aims to elucidate the mechanisms underlying CBM migration, encompassing diffusion and adsorption phenomena within the coal matrix, as well as interactions with adjacent strata. The outcomes of this study carry substantial implications for optimizing CBM extraction techniques and promoting the sustainable utilization of this invaluable natural resource.

KEYWORDS

Coalbed methane; pore-fracture double-porosity; seepage.

1. INTRODUCTION

Coalbed methane (CBM) represents one of the primary hazards to coal mine safety during mining operations, yet it also stands as a high-quality, clean, and efficient energy source. CBM, primarily composed of methane, is a form of unconventional natural gas generated during the coalification process and stored in coal seams predominantly through physical adsorption. The extraction process of CBM involves desorption from the coal matrix pores and seepage from fractures into wellbores. Consequently, with the extensive coal mining operations, there is an increasing depth of research into the coexistence, adsorption, diffusion, and infiltration mechanisms of coalbed gas.

In view of the unique reservoir structure of coal seam, the physical structure of coal rock reservoir and the production mechanism and distribution of coalbed methane are studied. The form is summarized. This research lays the groundwork for the coexistence and effective exploration and development of viscous gases within coal seams.

2. CBM RESERVOIR PROPERTIES AND PRODUCTION MECHANISMS

Coal seams serve as reservoirs for CBM, constituting a typical dual-porosity system characterized by a network of pores and fractures. They possess a large internal surface area, with highly developed microfractures and fracture systems. CBM exhibits three primary states: adsorbed, free gas, and dissolved gas. Approximately 80% to 95% of CBM exists in the adsorbed state within coal seams. Coal seams represent a typical dual-porosity medium with a system of micropores and macropores. Micropores are embedded within the coal matrix, while macropore systems consist of cleat systems surrounding the coal matrix. Coal cleats comprise face cleats and butt cleats, typically existing in orthogonal or near-orthogonal orientations to the coal seam, either perpendicular or nearly perpendicular.

2.1. Pore and fissure structure of coal

Matrix pores, also known as micropores, generally have diameters ranging between 50 to 100 nm. Micropores in coal reservoirs are highly developed, with the majority of CBM existing in the adsorbed state on the surfaces of these micropores. Due to their small diameters, micropore systems are typically considered to contain single-phase gases. Coal pores exhibit a wide range of diameters, from macroscopic fractures on the order of micrometers to pores so small that even nitrogen molecules cannot penetrate. The latest classification standards for pore sizes are detailed in Table 1.

Table 1. Types and characteristics of CBM pores

Pore types	characteristics	Reservoir mode	migration modes
seepage pore	Pore diameter greater than 100 nm, primary pore and variable pore	free gas	seepage
condensation-adsorption pores	The pore system encompasses molecular-scale interstitial pores with diameters ranging from 10 to 100 nm, as well as partially deformed primary pores and metamorphic gas-filled pores	adsorbed gas；condensed gas	diffusion
adsorption pores	The pore system comprises molecular-scale interstitial pores with diameters ranging from 2 to 10 nm.	adsorbed gas	diffusion
absorption pores	Pores with diameters smaller than 2 nm consist of organic macromolecular structural unit defects, some of which are molecular-scale interstitial pores	filling gas	diffusion

Fractures in coal are naturally formed. It is generally believed that there are two types of fracture systems in coal seams[1]. The first type is generated due to the uniform contraction of the coal's cementing material in volume during the coalification process, induced by factors such as temperature and pressure, resulting in internal tension, exhibiting mechanical properties with extensibility, known as cleats. Cleats are a prevalent type of endogenous fractures in coal seams and play a crucial role in CBM production. They represent a series of natural fractures formed in coal seams due to various processes such as desiccation, coalification, lithification, and tectonic pressure. The second type is induced by geological structures, known as "exogenous fractures." Based on the morphology and genesis of coal bodies, fractures are classified into three types: endogenous fractures, exogenous fractures, and inherited fractures.

Cleats (endogenous fractures): Cleats in coal seams are primarily formed as a result of changes in coal material structure and construction during the process of coalification. Cleats (endogenous fractures): Fractures in coal are caused by the structural and constructional changes of coal under the influence of coalification. Based on their morphology and characteristics at different levels, they can be classified into face cleats and butt cleats. Face cleats often run parallel or approximately parallel to the bedding planes and are mostly tabular, exhibiting good continuity, and are the primary endogenous fractures in coal seams. Butt cleats only develop between two face cleats and typically run perpendicular or approximately perpendicular to the bedding planes. They generally have poor continuity and irregularities within the fractures, making them secondary endogenous fractures. Both face cleats and butt cleats are developed in coal rocks, with small individual scales and high overall densities, displaying a three-dimensional network distribution, as illustrated in Figure 1.

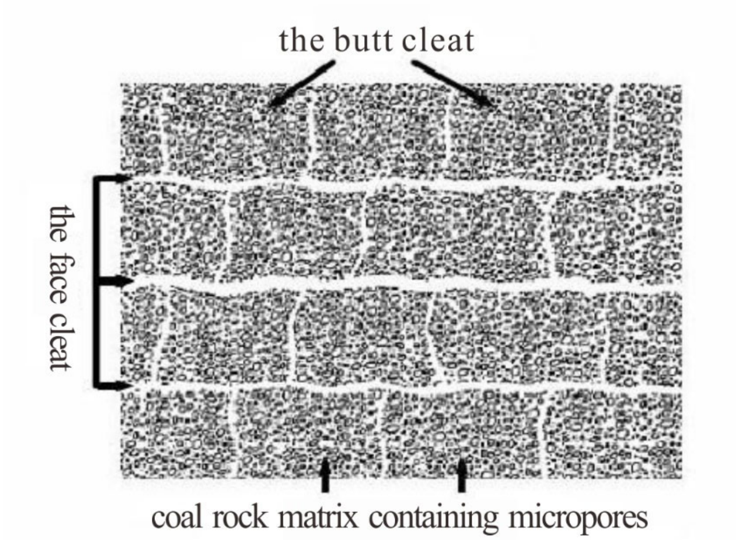

Figure 1. Cleat in coal rock

Exogenous fractures: Fractures formed in coal seams under strong tectonic stress are referred to as exogenous fractures. They can be categorized based on their origin into: exogenous shear fractures, tension fractures, and cleavage zones. Exogenous shear fractures may occur at any location within the coal seam and can intersect the coal seam at different angles, exhibiting feather-like or wavy striations. These fractures often have large intervals, with two fractures frequently coexisting simultaneously. Tensional exogenous fractures share similarities with rock joints and exhibit a "staggered" distribution pattern. Cleavage refers to a series of mutually parallel wavy fractures generated during interlayer slip in coal seams.

Inherited fractures: Inherited fractures possess a dual nature, combining characteristics of both cleats and exogenous fractures, making them transitional in type. If the direction of structural stress fields remains unchanged before and after cleat formation, earlier cleats will be further reinforced. This is manifested by some cleats extending and expanding from the coal seam where they developed to adjacent strata, while maintaining their original direction. These cleats are referred to as inherited fractures.

Results indicate that the surface-to-volume ratio of the coal matrix's micropore system is high, providing excellent adsorption properties but poor permeability. On the other hand, the fracture system within coal seams exhibits lower porosity and reservoir capacity but higher permeability, serving as significant pathways for fluid flow, including oil and gas migration. Therefore, the natural porosity and fracture density of coal are essential characteristics, directly influencing the adsorption capacity and storage properties of CBM.

2.2. Occurrence states of CBM

CBM exists in three basic forms: adsorbed, free, and dissolved states. These states are in a dynamic equilibrium process, with adsorption being the predominant form, accounting for 70%~95%, free gas around 10%~20%, and dissolved gas in minimal amounts. The specific proportions depend on factors such as the degree of coalification and burial depth. These states are in dynamic equilibrium; when pressure increases, free gas will adsorb onto the coal matrix, with a small fraction also dissolving, and vice versa.

Adsorbed CBM accounts for 75%~95% of the total methane content in coalbeds and is the primary occurrence state. Adsorbed methane primarily resides in the matrix pores of coal rocks. Methane adsorption on the coal matrix surface is a physical phenomenon. Current adsorption theories include single-layer adsorption theory, multi-layer adsorption theory, and adsorption potential theory. Extensive research both domestically and internationally indicates that coal exhibits single-layer physical adsorption of gases such as methane. The adsorption isotherm[2] is depicted in the following Figure 2.

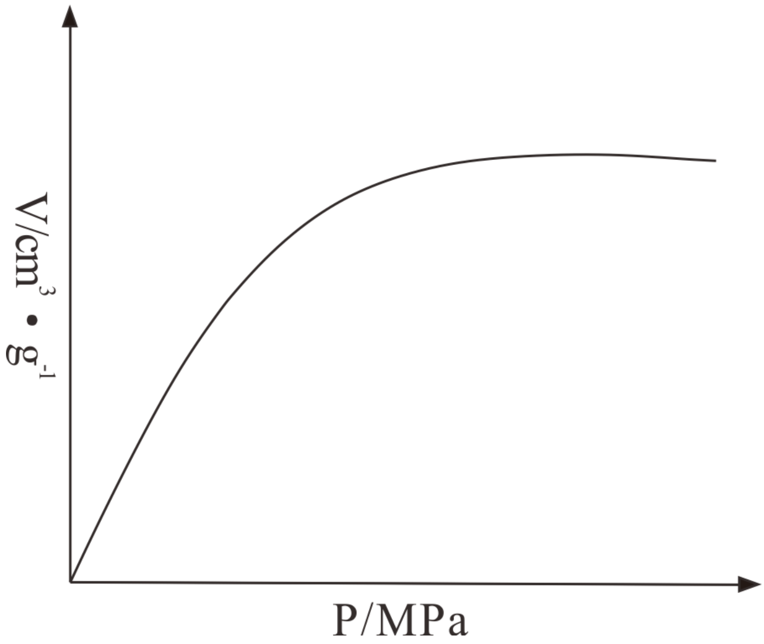

Figure 2. Adsorption isotherm

The adsorption isotherm curve indicates that as reservoir pressure P increases, the adsorption volume V continually increases, facilitating the adsorption accumulation of CBM. Once the pressure decreases continuously, adsorbed gas molecules will desorb from the inner surface of coal and transition to the free state. Free gas typically accounts for around 10%-20% of the total CBM content. In the free state, CBM exists as free gas within the cleats and other fracture systems of coal, capable of freely moving within these fracture systems in the presence of pressure gradients. Coal rock reservoirs are often saturated with formation water; therefore, under certain pressures, a portion of CBM will inevitably dissolve in the formation water, termed dissolved gas.

The production of CBM is jointly controlled by the processes of desorption, diffusion, and percolation, with these three stages closely interconnected, influencing and restraining each other. Any limitation in one process severely affects the production of CBM. Percolation is a prerequisite for desorption; with percolation, pressure decreases, leading to desorption. Pressure gradients during percolation create concentration differences in methane molecules within the pathways, facilitating diffusion under these concentration gradients. Micro-pores in coal seams rapidly release the adsorbed gas. Simultaneously, desorption of CBM causes coal blocks to shrink, increasing fracture width and enhancing coal seam permeability, which benefits methane percolation. Diffusion acts as a bridge between desorption and percolation, with unimpeded percolation accelerating diffusion, while rapid methane diffusion promotes desorption.

3. RESEARCH ON THE PERMEATION MECHANISM OF CBM

CBM enters the fracture system through diffusion within the coal medium and then desorbs through the internal surface of the coal. Due to the weak permeability of micro-pores in coal, the permeation of CBM within the coal is often overlooked, with migration primarily assumed to occur through diffusion or mass transfer. Migration essentially involves the movement of gas from regions of high polymer density to regions of low molecular density under concentration gradients. Regions of high polymer density serve as desorption zones for CBM, while permeation pathways represent areas of low molecular concentration. The distribution of CBM within the coal can be classified into quasi-stable and non-stable types, both following Fick's law. Regardless of the diffusion mode, it is determined by the concentration within the substrate, initially consistent with the pressure of free gas in the fracture system. The extraction process of CBM has a certain impact on the original equilibrium state of the coal seam, with density and pressure differences being the main factors influencing diffusion and permeation of CBM. The desorption-diffusion-percolation stages occur synchronously. In each unit volume of coal matrix, the gas exchange per unit volume is equivalent to a uniform endogenous source, being discharged from the pore system and entering the fracture system. Figure 3 illustrates the coal seam fracture permeability test apparatus used under laboratory guidance.

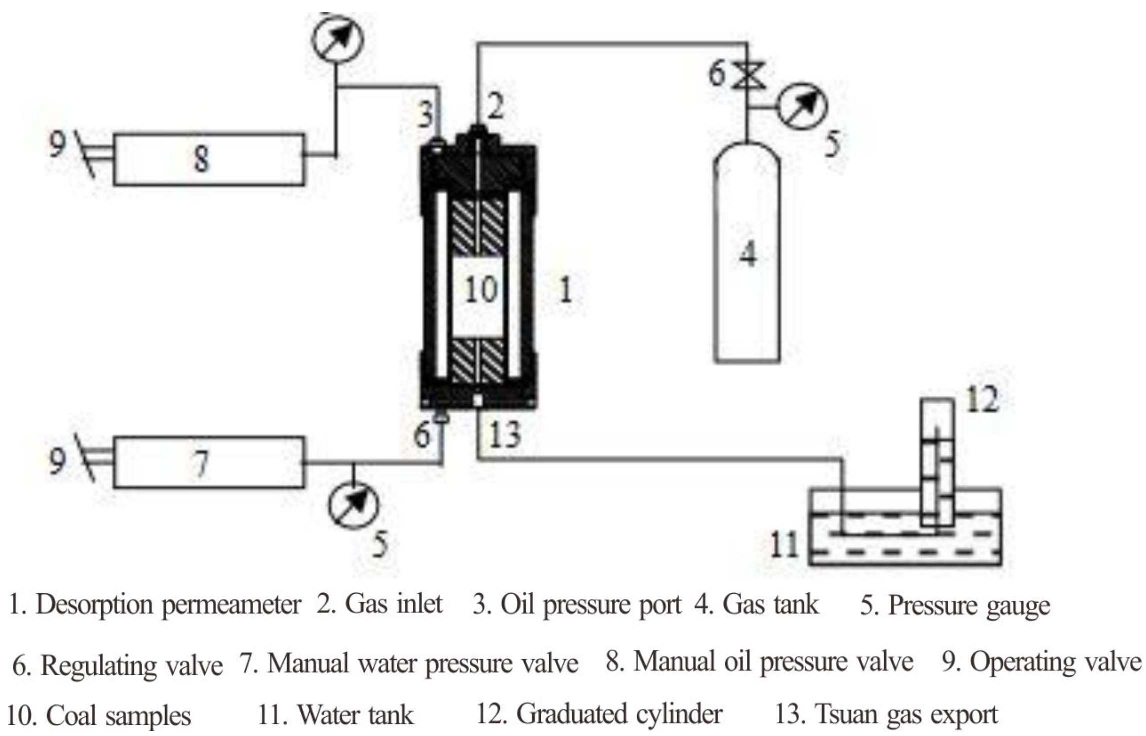

Figure 3. The schematic diagram of the instrument for measuring coal pore fracture permeability

3.1. CBM permeation theory

The permeation of CBM mainly occurs within fractures and cleats. Therefore, the permeability of fractures is an essential parameter for analyzing CBM permeation. It is also a critical indicator of the difficulty level of gas extraction and one of the main parameters for calculating theoretical gas emission rates. The permeability of coal rock reservoirs is controlled by various factors, with the most direct influence being the development characteristics of fractures/cleats in the reservoir. As the CBM well's dewatering pressure reduction progresses, it disrupts the original pressure equilibrium state of the coal reservoir layer, prompting CBM permeation. The CBM desorbed from the coal flows within the flow field, forming an elliptical-shaped flow field. The CBM continuously desorbed from the fractures near the CBM well flows into the bottom of the well, gradually reducing the pressure within the flow field and decreasing the chemical potential below that of the adsorption phase. This disruption of the original adsorption equilibrium state prompts the methane adsorbed in the micro-pores of the coal matrix to continuously desorb and become free gas participating in the permeation process through the fractures. Because the adsorption potential of methane gas in the adsorption phase is higher than that in the free state, it remains in an unbalanced state, ensuring the continuous desorption of adsorbed CBM and its flow towards the CBM well. The flow of methane in the fractures of coal reservoirs occurs under the drive of pressure differences and can be considered as linear flow, following Darcy's law.

3.2. Factors influencing CBM permeation

To better develop CBM and improve methane recovery rates, it is essential to understand the main influencing factors during the desorption process of coalbed gas. These factors can be broadly categorized into internal and external factors. Internal factors pertain to the physical properties of the coalbed itself, such as its composition and structure, while external factors include temperature, pressure, moisture content, and gas composition.

(1) Material Structure: The components of coal mainly consist of minerals and organic matter, with the carbon content of organic matter playing a dominant role in the adsorption capacity of coalbeds. The adsorption capacity increases with the rise in organic carbon content but decreases with the increase in other mineral content. Studies have shown that carbon has the strongest adsorption capacity, followed by bright and dull coal.

(2) Carbon Content: The porosity of coal blocks increases with the increase in coal rank, particularly the increase in microporosity, which enhances the surface area and adsorption capacity of the coal. Generally, the better the micro-pore structure of coal blocks, the better the separation and adsorption capacity. Under the same temperature and pressure conditions, the adsorption capacity of coal increases with the increase in carbon content.

(3) Molecular Concentration (Gas Content): The concentration gradient is the most crucial parameter for characterizing the diffusion characteristics of coalbed gas and non-steady-state dynamic equilibrium simulation. Typically, there is a positive correlation between concentration gradient and diffusion rate. During development, the gas content in coalbeds depends primarily on the coalbed's hydrocarbon generation capacity, adsorption, and desorption effects, as well as its micro-pore structure attributes. Methane gas desorbed from dewatering first stores in the matrix pores of coalbeds, with fractures mainly serving as transport channels. Therefore, in general, gas saturation in matrix pores is higher than in fractures. As dewatering progresses, coalbed gas gradually diffuses through the fissure system and percolates to the well for extraction[3].

(4) Temperature: With constant confining pressure, axial pressure, and pore pressure, the permeability of samples gradually decreases with increasing temperature. Under the influence of temperature, strains occur in the internal cracks of coalbeds when the temperature reaches a certain level. The fractures in the coal, which are the transport channels for gases, undergo compression due to pressure, resulting in reduced mobility of coal. Although higher temperatures enhance the desorption capacity of coal, their relative impact on fractures is much smaller. Thus, the higher the temperature, the lower the permeability of coalbed gas. This understanding represents a new perspective on the effect of temperature on coal sample permeability.

(5) Effective Stress: During loading pressure, i.e., the process of increasing axial and pore pressures, permeability increases exponentially with increasing axial and pore pressures at the same temperature. During unloading of coal, i.e., the process of reducing axial and pore pressures, effective stress exhibits a parabolic relationship with permeability and permeability coefficients. That is, as axial and pore pressures decrease, effective stress decreases continuously, and permeability and permeability coefficients first decrease and then increase.

4. APPLICATION EXAMPLE — HYDRAULIC FRACTURING TO ENHANCE PERMEABILITY

In many regions of China, the permeability of coal seams is often low, typically less than 1 $\times 10^{-3}$ um^2. This limits the extraction of CBM to only the immediumte vicinity of the wellbore during surface drilling. Although there may be initial production, the poor permeability of coal seams results in limited gas flow and pressure propagation, leading to rapid production decline and low yields in areas further from the wellbore. Therefore, hydraulic fracturing followed by surface dewatering is employed to enhance the productivity of CBM wells[4].

After completion, the reservoir section of the well is sealed using sealing devices to create a closed system. High-pressure, high-flow pumps are utilized at the surface to inject a liquid (often fresh water or slickwater) with a certain viscosity into the coal seam at rates significantly exceeding the absorption capacity of the coal. This creates ultra-high pressures within the wellbore. As the liquid pressure increases, fractures begin to form at the weakest points around the wellbore, overcoming the stress of the strata and the strength of the coal itself. Continued injection of the fracturing fluid causes these fractures to propagate further into the reservoir. Once a network of large fractures is established, a proppant-laden slurry (usually containing quartz sand or ceramic beads) is injected to support and keep the fractures from closing completely[5].

Finally, displacement fluid is injected into the wellbore to displace the proppant-laden slurry from the wellbore into the fractures. This process, known as hydraulic fracturing or "fracking," increases the permeability of the coal seam, allowing for improved extraction of CBM from larger areas surrounding the wellbore.

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