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Research Progress on Evolution of Coal-Water Contact Angles and Mechanisms of Wettability Regulation: From Theoretical Foundations to Field Applications

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Abstract

The gas present in coal seams can alter the coal-water interface properties through adsorption, yet a systematic understanding of its underlying mechanisms remains lacking. This review systematically examines the factors influencing coal wettability in gas-bearing atmospheres, with a focus on the regulatory effects of physicochemical properties of coal—such as coal rank, pore structure, mineral composition, and functional groups. It further elucidates the mechanisms by which strongly adsorbing gases like CH_4 and CO_2, as well as weakly adsorbing gases such as N_2 and He, affect the coal-water interface. The practical applications of related theories in field settings, such as optimizing coal seam water injection processes and improving dust suppression efficiency, are also summarized. This study aims to provide a theoretical foundation for advancing the understanding of coal-water wetting mechanisms in gas-bearing environments and to support the optimization of related engineering practices, thereby contributing to safer and greener coal mining operations.

Keywords

Gas-bearing atmosphere; Coal-water contact angle; Wettability; Gas adsorption; Coal dust control.

1. Introduction

The wettability of coal, as an important physical and chemical characteristic of the coal surface [1], holds significant research value in fields such as dust control and prevention of gas disasters. After wetting treatment, the coal mass can significantly reduce occupational diseases such as pneumoconiosis and silicosis caused by inhaling dust. Therefore, the wettability of coal directly determines the feasibility of coal seam water injection technology and the effectiveness of mine dust control [2].

However, most of the classic theories on coal wettability studied by scholars are based on the coal-water two-phase system. Nie Baisheng et al. [3] proposed that the interaction between water and coal includes two aspects: the wetting of coal by water and the adsorption of water by coal. The applications to change the wettability of coal are also in a two-phase environment: Song Jinxing et al. [4] reduced the capillary pressure of coal reservoirs through surfactant fracturing fluid; Franco-Aguirre M et al. [5] changed the wettability by forming a nano-flow with the synergistic effect of SiO_2 nanoparticles and anionic surfactants; Jiang Wei et al. [6] affected the production of coalbed methane and the return efficiency of fracturing fluid by reducing surface tension and increasing contact angle; Wang Wenbin [7] and Zhou Qun [8] et al. changed the wettability by magnetizing water or adding surfactants. However, this is far from the real coal seam environment. The coal seam underground is a complex system where gas, water, and coal coexist. Among them, Yang Jing [9] et al. were the first to systematically clarify through the combined use of infrared spectroscopy, electrophoresis, and forward osmosis experiments that the wetting performance of solutions on coal dust not only depends on the gas-liquid surface tension but more crucially on the solid-liquid interfacial tension. However, current research on this is still scattered, making many conclusions difficult to directly apply in the variable underground environment.

Based on this, this paper systematically reviews and integrates the research on the wetting mechanism of coal-water under a gas atmosphere. It examines the influence of intrinsic properties such as coal rank, porosity, and surface functional groups on wettability; focuses on the adsorption behavior of gas components such as CH_4 and CO_2, and systematically deconstructs the core mechanism of forming microscopic gas films to dominate interfacial wetting; and then discusses the progress and limitations of these theories in guiding on-site dust control and gas drainage applications, to assist in the safe production and green development of coal mines.

2. The Core Regulatory Mechanism of Gas Component Adsorption on Wettability

The wetting effect of coal seams is a key factor in the prevention and control of gas and dust, with the core being the wetting ability of water on the coal surface, which is usually quantified by the contact angle between coal and water [10]. Under deep mining conditions, the coal body is actually in a complex "gas atmosphere" mainly composed of CH_4 and including components such as CO_2 and N_2, and its wetting behavior is fundamentally different from that in an air environment. Research shows that strongly adsorptive components in the gas (such as CH_4 and CO_2) can significantly interfere with the properties of the coal-water interface through competitive adsorption and other means, and their influence far exceeds that of weakly adsorptive gases such as He and N_2 [11]. Therefore, to accurately understand the true wetting characteristics of deep coal seams, the research perspective must shift from a single gas to the real "gas atmosphere". For this reason, this chapter will follow the analytical path from the adsorption characteristics of a single gas to the competitive and synergistic effects of multiple components, and simultaneously clarify the unified mechanism of the gas film effect, systematically revealing its interface regulation mechanism.

2.1. The adsorption characteristics and independent regulation mechanisms of the main component gases of gas

Strongly adsorptive components such as CH_4 and CO_2 can form stable adsorption layers on the coal surface due to their strong adsorption capacity. Among them, the adsorption of CH_4 mainly relies on van der Waals forces, while the adsorption of CO_2 involves electrostatic interactions with oxygen-containing functional groups [12]. This is the physical basis for their ability to dominate the coal-water wetting property. Current research generally believes that the regulation mechanism mainly stems from three aspects: the physical barrier effect of the gas adsorption film on the water phase (see Figure 1), the change in the surface free energy of the coal, and the unique pore structure modification effect of CO_2. The following text will combine the specific adsorption characteristics of CH_4 and CO_2 to conduct an in-depth analysis of these mechanisms.

2.1.1. Adsorption Characteristics and Hydrophobicization Mechanism of Methane

Methane, as the main component of coal seam gas, has a strong adsorption capacity for coal. This adsorption characteristic is closely related to the change in the coal-water contact angle. Based on the research of many scholars, it will be systematically analyzed from three dimensions: adsorption characteristics, macroscopic phenomena, and core mechanism.

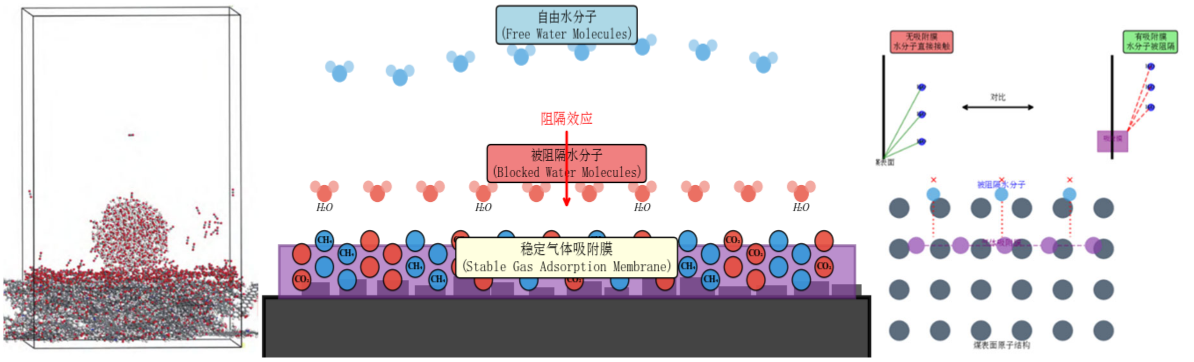
In terms of adsorption characteristics, the adsorption of CH4 by coal conforms to the Langmuir isothermal line characteristics. Its complex pore structure (containing abundant micropores, mesopores, and macropores) provides a large surface area for CH4 adsorption. The adsorption process is dominated by the filling of micropores. At a certain temperature, the methane adsorption amount increases with the increase in partial pressure and tends to saturation. Zhang Qun et al. [13] conducted high-pressure isothermal adsorption experiments of different coal grades under high-pressure conditions and derived a temperature-pressure comprehensive adsorption model for coal adsorption of CH4, revealing the temperature-pressure comprehensive adsorption model of CH4 by coal. The model prediction results were in good agreement with the experimental data. Yang Feng et al. [14] concluded that CH4 preferentially occupies high-energy adsorption sites (such as micropores). From a thermodynamic perspective, the calculated equivalent adsorption heat was 11.67~16.62 kJ/mol (average 14.58 kJ/mol), which is typical of physical adsorption.

At the macroscopic phenomenon level, the coal-water contact angle in the CH4 environment shows significant pressure dependence and coal grade sensitivity. In 2022, Wei Jianping et al. [15] first established a test system for coal-water wetting angle under gas atmosphere conditions, quantitatively revealing the differences in wetting properties between anthracite (with the contact angle increasing from 72.99° to 106.90°) and bituminous coal under methane pressure of 0-2 MPa, and the rules of the transition from hydrophilic to hydrophobic. This laid an experimental foundation for the research on the regulation of coal-water interface behavior by methane adsorption.

The core regulation can be elaborated from multiple aspects: Firstly, in terms of the adsorption membrane blocking effect, CH4 forms a physical adsorption layer through van der Waals forces. Although this adsorption layer is relatively thin and has a weak blocking effect [16], it is still the basic physical mechanism for its hydrophobicization; Secondly, from the perspective of surface free energy regulation, CH4 adsorption mainly reduces the non-polar component of the coal surface free energy, thereby enhancing the hydrophobicity of the coal; Finally, at the microscopic level of functional groups, the types of functional groups on the coal matrix surface have significant differences in CH4 adsorption behavior, thereby affecting its hydrophobicization effect. Specifically, the research of Zhang Jin [17] and Jia Jinzhang [18] both adopted a research method combining molecular simulation and experimental analysis, and clearly pointed out that non-polar aliphatic functional groups (such as -CH_3) and nitrogen-containing functional groups (such as -NH_2) are favorable sites for promoting CH4 adsorption; In contrast, oxygen-containing functional groups usually exhibit a tendency to inhibit CH4 adsorption. These systematic microscopic studies have powerfully explained the intrinsic reason for the significant differences in wetting properties among coal grades with different chemical compositions.

2.1.2. Adsorption Characteristics and Hydrophobicization Mechanism of Carbon Dioxide

The adsorption capacity of carbon dioxide in coal is significantly stronger than that of methane, and its influence on the behavior of the coal-water interface is more complex and intense. Jin Xing et al. [19] demonstrated that this characteristic is mainly due to the tetrahedral moment structure of CO_2 molecules, which enables it to form strong electrostatic interactions with oxygen-containing functional groups on the coal surface. Its adsorption behavior conforms to the Langmuir model and strengthens with the increase in vitrinite content. Song Ge et al. [20] further confirmed through experiments that the adsorption capacity of coal for CO_2 can reach 2.68 to 3.26 times that of CH_4 under the same conditions, showing a stronger adsorption potential.



(a) (b)

Figure 1. Schematics illustrating the barrier effect under different conditions ((a) Plot the gas film under single-component gas simulation using MS (b) The barrier effect in the competitive adsorption environment of CO_2 and CH_4)

In terms of macroscopic wetting behavior, Han Sijie et al. [21] found that the adsorption behavior of supercritical CO_2 is affected by multiple factors, and its adsorption curve shows abnormal behavior near the critical point due to the drastic change in fluid density; Wang Jianmei et al. [22] pointed out that the adsorption amount of supercritical CO_2 on anthracite changes abruptly at the critical pressure, and the modification of the coal's chemical structure and pores is the key factor causing the drastic change in wetting properties.

At the mechanism level, the strong wetting regulation ability of CO_2 is reflected in three aspects: Firstly, Zhou Lai et al. [16] and Li Yundong et al. [23] pointed out that CO_2, with its tetrahedral moment and higher adsorption enthalpy, can form a thicker and denser adsorption layer than CH_4, thereby generating a stronger physical barrier effect; Secondly, Li Zewen et al. [24] found that CO_2 adsorption can significantly reduce the polar component of the free energy on the coal surface, effectively shielding the surface hydrophilic sites, which indirectly confirms the stronger interaction between CO_2 and polar sites, which is the key to its better hydrophobic effect; Moreover, Zhang Kun et al. [25] experimentally simulated and demonstrated that CO_2 injection would significantly change the volume parameters and pore structure of the coal body by causing the organic matter in the coal to expand. This is the same as the theory revealed by He W et al. [26] regarding the dissolution of minerals by supercritical CO_2. In 2018, Xiaoxiao Sun [27] first used NMR relaxation method to study the CO_2-water wetting property of coal, revealing the influence law of supercritical CO_2 on the coal-water interface tension, introducing new technical ideas for the subsequent experimental methods of wetting regulation in multi-component gas atmospheres. Under the joint action of these complex regulatory mechanisms, CO_2 exhibits a far stronger regulatory intensity and complexity in the wetting property of coal-water interface compared to CH_4.

2.1.3. Comparison of Methane and Carbon Dioxide Regulation Mechanisms

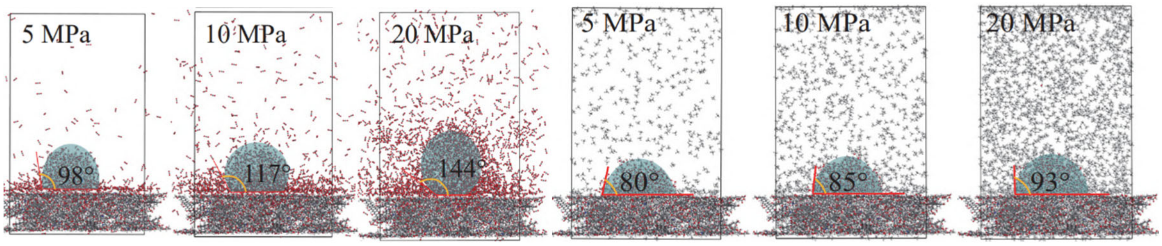
Based on the aforementioned analysis， although CH_4 and CO_2 are both strong adsorption components in gas, their behavior patterns and regulatory mechanisms at the coal-water interface are fundamentally different.

This difference is primarily rooted in the strength of molecular interactions： thermodynamic analysis indicates that the initial isothermal adsorption heat of CO_2 by coal is significantly higher than that of CH_4， confirming that the interaction force of the coal matrix surface on CO_2 molecules is stronger. Correspondingly， the reduction in the surface free energy (especially the polar component) of coal after adsorbing CO_2 is also greater， which reveals the intrinsic reason that CO_2 has a higher adsorption capacity per unit area of coal surface from the energy perspective. When they coexist， this difference in interaction force directly translates into the competitive adsorption advantage. Studies have shown that in CO_2/CH_4 mixed gas， the isothermal adsorption heat of CO_2 remains high and further increases with the increase in its concentration， while the adsorption of CH_4 is significantly inhibited [28]. The latest research further confirms that CO_2 exhibits significant adsorption selectivity for CH_4， and this selectivity coefficient continues to increase with the increase in pressure [29]. This clearly indicates from the kinetic perspective that CO_2 occupies an indisputable dominant position in adsorption in the real gas environment， especially under high pressure conditions. The core dimension comparison is shown in Table 1.

Table 1. Comparison of the core dimensions of methane and carbon dioxide

Core dimension	**Methane (CH_4)**	**Carbon dioxide (CO_2)**	**Mechanism connotation explanation**
Action mode	Competitive occupation	Competitive occupation + physical and chemical modification	CO_2 has an additional dimension of "transforming coal itself" compared with CH_4, and its effect is more fundamental.
Interface regulation	Reduce non-polar surface energy	Significantly reduce polar surface energy	CO_2 can more effectively shield coal hydrophilic sites, which is the chemical root of its strong hydrophobic effect.
Macro effect	Pressure-dependent hydrophobic film	Strong hydrophobic film + pore structure reconstruction	CO_2 can sustainably affect wettability by changing pore structure, while CH_4 effect disappears with pressure relief.

The above comparison reveals a fundamental rule: In a gas atmosphere, the ability of gas components to regulate wettability depends on their adsorption strength and the diversity of their mechanisms. CH_4 mainly acts as a hydrophobic covering agent, reducing surface energy through physical adsorption; while CO_2 assumes the roles of "covering agent", "chemical modifier", and "porosity structure modifier" simultaneously. This fundamental difference enables CO_2 to exhibit much greater intensity and complexity in the multi-coupled regulatory pathways compared to CH_4.



(a) (b)

Figure 2. Comparison of contact angles in CO_2 and CH_4 environments

((a) Coal-water equilibrium wetting angle in a CO_2 environment;(b) Coal-water equilibrium wetting angle in a CH_4) (Si et al. [30])

These significant individual differences indicate that when they coexist in mine gas, they will inevitably trigger complex competitive adsorption behaviors, which will become the core for regulating the wettability state of the coal-water interface, rather than the independent effects of each component.

2.2. Reference Role of Weakly Adsorbed Components and Inert Components

2.2.1. Limited Influence of Weakly Adsorbed Components on Wetting Properties

Weakly adsorbed components (with nitrogen as a typical example) exist in coal in a different state and mechanism from strongly adsorbed gases. The main difference is that they have weak adsorption capacity and their influence on the coal-water contact angle is mainly physical.

In terms of adsorption characteristics, nitrogen is a weakly adsorbed gas. Its molecular polarity is weak, and the interaction force with the coal surface is mainly dispersion force. The adsorption amount is much lower than that of CO_2 and CH_4. This difference in adsorption capacity directly leads to different existence states of these weakly adsorbed gases in coal pores. Weakly adsorbed gases are more likely to exist in free state in larger pores and fractures. Under high pressure, nitrogen squeezes the free water in coal pores, making the water film distribution less uniform. To some extent, this affects the water penetration in coal pores, indirectly causing the measurement value of the contact angle to fluctuate slightly, but not changing the inherent wetting property of the coal surface.

At the macroscopic phenomenon level, the coal-water contact angle under nitrogen environment shows a slight increase with the increase of pressure, and there is no significant hydrophilic-hydrophobic transition. Jiang Wei et al. [31] mainly studied the substitution effect of nitrogen on methane in coal. Through two experimental conditions of high-pressure injection and isobaric diffusion, they analyzed the rules and mechanism of nitrogen replacing methane in coal and revealed the influence of nitrogen under different conditions on methane substitution in coal, providing a theoretical basis for the technology of injecting nitrogen for extracting/flushing out coal seam gas in underground mines.

Overall, in the gas atmosphere, the influence of weakly adsorbed components (nitrogen) on the coal-water contact angle is much weaker than that of strongly adsorbed gases. Its effect mainly manifests as physical pressure effect and slight competitive adsorption, without significant surface energy regulation or adsorption film blocking.

The section headings are in boldface capital and lowercase letters. Second level headings are typed as part of the succeeding paragraph (like the subsection heading of this paragraph). All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. When receiving the paper, we assume that the corresponding authors grant us the copyright to use.

2.2.2. Reference role of inert components on wettability

Helium, as a typical inert gas, hardly undergoes chemical reactions with the surface of coal and has extremely weak interaction forces, thus having a very weak adsorption capacity in coal. Under various temperature and pressure conditions, the adsorption amount of helium in coal is extremely low and can be almost negligible, being a single atomic molecule, mainly existing in the coal pores in a free phase.

Wei Jianping et al. [15] observed that within the helium pressure range of 0 to 2 MPa, the contact angle of anthracite (CZ sample) increased from 72.99° (0.1 MPa) to approximately 80.31° (2.0 MPa), an increase of about 7.32°, which was in sharp contrast to the contact angle of methane (CH_4) increasing from 72.99° to 106.90°, an increase of 33.91°. It was also clearly pointed out that helium, as a non-adsorptive gas, does not form an air film on the coal surface or significantly reduce the surface free energy of coal like methane (CH_4). The main reason for the slight increase in the contact angle caused by helium pressure is the mechanical compression effect of the environmental pressure on water droplets. High-pressure environments will resist the spreading trend of water droplets and mechanically delay their spreading kinetics, thereby causing an increase in the apparent contact angle. However, this does not change the inherent chemical hydrophilicity of the coal body. Chen Jiuyu et al. [32] studied that the properties of He molecules are stable and have no effective adsorption on the coal surface, only slightly affecting the spreading kinetics of water droplets through physical pressure, and cannot occupy the hydrophilic sites on the coal surface like CO_2, nor will it change the physical and chemical properties of the coal surface (such as surface energy, functional group characteristics, etc.), and has no substantive regulatory effect on the equilibrium contact angle. Therefore, the helium environment is often used as a control experiment to eliminate the pure pressure effect and highlight the essential differences in the influence of adsorptive gases and non-adsorptive gases on the coal-water contact angle.

Although in some experiments involving gas displacement, helium, due to its higher diffusion ability and lower viscosity, may affect the distribution state of the original gas and water in the coal pores, indirectly having a weak influence on the coal-water contact angle, compared to gases with adsorption properties, this indirect influence is very limited and does not have a substantial impact on the coal's water absorption and wettability.

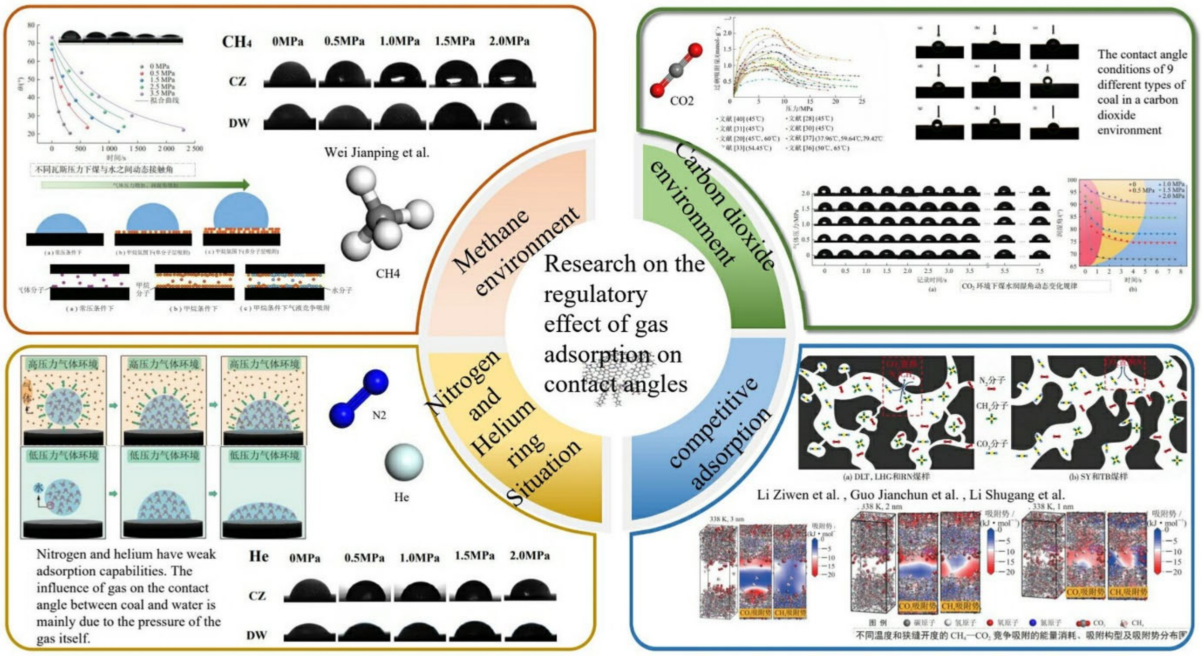


Figure 3. Schematic summary of gas adsorption effects on the contact angle

2.3. The Regulatory Mechanism of Contact Angle by Multi-component Gases

Under the real gas environment, the evolution of the coal-water contact angle is not a simple superposition of the effects of a single gas, but rather a complex interface reconfiguration process achieved through the competitive adsorption of multiple components. The core lies in the differential occupation of the limited adsorption sites on the coal surface by different gas molecules, and ultimately, it achieves the coordinated regulation of wettability by changing the interface properties.

The physical essence of this process is the competitive occupation of adsorption sites. In 2020, Wei Yong et al. [33] used molecular dynamics simulation methods to reveal that CO_2 significantly changes the contact angle of water in organic matter nanochannels, while CH_4 has a smaller effect, and the contact angle increases linearly with the increase in CO_2 volume fraction. They first proposed the mechanism of CO_2 dominating interface reconfiguration through competitive adsorption from the nanoscale. This phenomenon stems from the antagonistic effect of CO_2 on CH_4 adsorption - the CO_2 molecules have stronger affinity to the coal surface and can preferentially occupy high-energy adsorption sites, thereby enhancing the hydrophobicity of the coal surface. Guo Jianchun et al. [34] conducted molecular simulation studies on high-grade coal in the Qinshui Basin, revealing this mechanism from the perspective of interaction energy. They found that CO_2, due to stronger electrostatic and van der Waals forces with the surface of coal molecules, can preferentially occupy adsorption sites and significantly reduce the adsorption amount of CH_4. In 2011, Zhou Lai et al. [16] conducted systematic thermodynamic analysis and calculated that the isosteric adsorption heat of CO_2 is significantly higher than that of CH_4, and they clarified that the root cause lies in the strong electrostatic interaction between the quadrupole moment of CO_2 and the functional groups of the coal surface, providing a profound theoretical explanation for the competitive adsorption behavior of multiple gases and its regulation mechanism of wettability.

The direct result of interface reconfiguration caused by competitive adsorption is the change and reorganization of the free energy on the coal surface. Zhao Danan et al. [35] studied that the adsorption capacity of anthracite for CO_2, CH_4, and N_2 decreases successively, and the adsorption behavior of each component will change with temperature and pressure conditions, thereby affecting the final surface energy state. In a multi-component gas system, the change in contact angle essentially results from the dominance of high-affinity gases (such as CO_2) in controlling the surface energy reconfiguration through competitive adsorption. The preferred occupied adsorption sites are usually associated with the hydrophobic regions of the coal surface, and their occupation behavior directly reduces the interaction energy at the coal-water interface, leading to an increase in the contact angle.

From a mechanistic perspective, the competitive adsorption effect refers to high-affinity gases (such as CO_2, CH_4) occupying the active sites on the coal surface with stronger affinity, repelling water molecules from contacting, resulting in an increase in the contact angle (hydrophobicization). The surface energy reduction effect is manifested as the adsorbed gas molecules weakening the polarity of the coal matrix surface and reducing the solid-liquid adhesion work. Zhou Lai [16] evaluated the preferential adsorption of CO_2 in coal layers under different temperatures and the competitive adsorption mechanism with CH_4, finding that the adsorption force of CO_2 on coal is stronger than that of CH_4, providing an essential theoretical explanation for the above effect.

Therefore, the regulation of contact angle by multi-component gas components is essentially based on the differences in adsorption affinity, driven by competitive adsorption to control the surface energy reconfiguration, and ultimately forming a functional gas film, manifested as a directional change in wettability. This mechanism not only clarifies the intrinsic relationship between the proportion of gas components and the response of contact angle, but is also crucial for providing a key theoretical basis for optimizing the injection gas ratio (such as using CO_2 to drive CH_4 desorption) in coal seam gas extraction to enhance methane recovery rate. It effectively expands the single-gas adsorption theory to engineering applications in complex multi-component systems.

2.4. Film effect: Interface manifestation of competitive adsorption and wetting inhibition

The final physical outcome of competitive adsorption behavior in a gas atmosphere is the formation of a dynamic and heterogeneous "composite gas film" at the coal-water interface. This gas film is the macroscopic manifestation of the competitive result: the components with stronger adsorption potential (such as CO_2) form a dense adsorption layer at the dominant sites, while the components with weaker adsorption potential (such as CH_4, N_2) are distributed at secondary sites or pore spaces, jointly constituting a physical barrier, as shown in Figure 4.

The physical essence of the film is the formation of a nanoscale adsorbed state gas layer on the surface of coal-rock micropores. Li Shugang et al. [36] revealed through molecular simulation the thermodynamic basis for its formation: the adsorption capacity and heat of adsorption of multi-component gases follow the relationship $CO_2 > CH_4 > N_2$, while the adsorption potential energy is $CO_2 < CH_4 < N_2$. This thermodynamic feature determines the spatial distribution and adsorption stability of different components in the gas film under the gas atmosphere, confirming the advantage of CO_2 in forming a stable gas film from an energy perspective.

The formation and dynamic characteristics of the film are regulated by environmental conditions and the properties of the coal body. Wei Jianping et al. [15] found that the gas film formed by methane adsorption on the coal surface would strengthen with increasing pressure, inhibiting water molecule contact through a dual mechanism of reducing the free energy of the coal surface and occupying the adsorption sites. In 2025, Si Leilei et al. [30] further confirmed that the gas adsorption performance and pressure jointly promote the thickening of the gas film, thereby hindering the contact of water molecules with the coal body and significantly reducing wettingness. This gas film acts as a physical barrier, blocking the contact of water molecules with the coal surface functional groups and reducing the surface free energy, synergistically promoting the coal body to transform from hydrophilic to hydrophobic, systematically elucidating the inhibitory mechanism of the gas adsorption layer on the wetting process, and laying a microscopic theoretical foundation for in-depth analysis of the "dynamic attenuation" phenomenon of coal wettingness under the gas atmosphere. Yue Jiwei [37] also found that the gas pressure not only increases the thickness of the gas film but also significantly enhances its structural stability, causing the spreading of water on the coal surface to increase exponentially, and the wetting effect to significantly decrease. In contrast, non-adsorptive gases, due to their lack of competitive adsorption ability, can only exert a weak compressive effect on droplets through environmental pressure, and cannot form an effective gas film.

The inhibition of wetting by the film follows a clear "adsorption-driven - structural response - performance mutation" hierarchical mechanism. First, it directly blocks the contact of water molecules with the oxygen-containing functional groups of the coal matrix; second, it reduces the free energy of the coal surface to weaken the solid-liquid adhesion work. Zhang Yanru et al. [38] studied the drag reduction mechanism of the active gas film at the micro-nano fluid-solid interface through molecular dynamics simulation, indicating that the formation of the gas film can significantly reduce the interface shear stress, and when the gas film reaches a certain thickness, the drag reduction effect becomes stable. This indicates that the formation and thickness of the gas film have a significant impact on wettingness, and is related to the inhibitory effect of the gas film on wettingness. Chen Liwei [39] studied the influence of water on the adsorption of CH_4 and CO_2 by coal, finding that the inhibition rate of water on the adsorption of CH_4 is always greater than that on CO_2. This indicates that water has a greater inhibitory effect on the weakly adsorptive gas adsorption by coal, and is related to the "adsorption potential energy threshold rule", that is, gases with higher adsorption potential energy (such as CH_4) are more likely to form a gas film, thereby inhibiting wettingness.

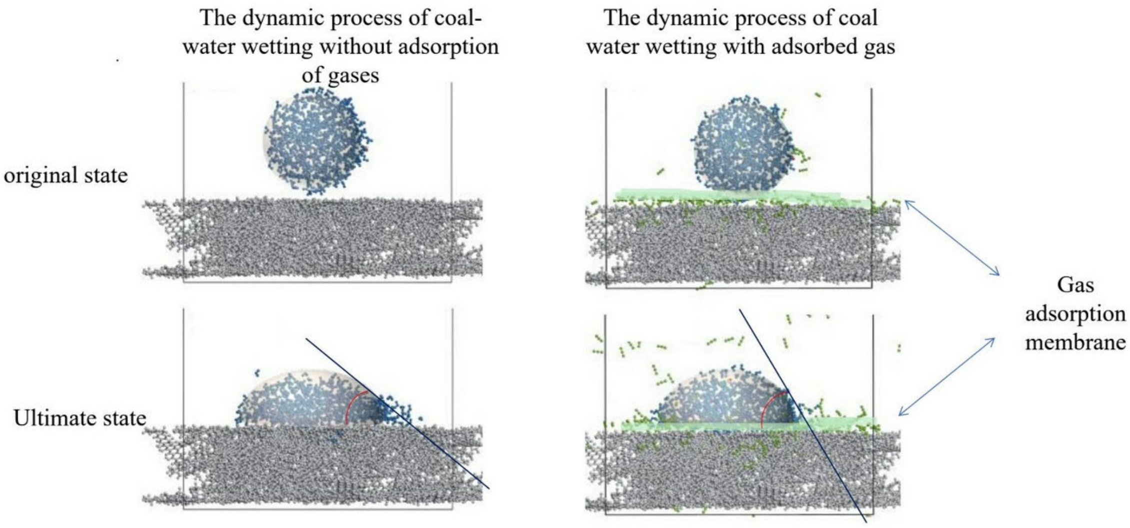


Figure 4. Comparative Analysis of Gas Film Formation and Wetting Inhibition Effects

The gas film effect, as the ultimate manifestation of competitive adsorption, achieves the inhibition of wettability through both physical barriers and energy regulation. From multi-component competitive adsorption to the formation of composite gas films, and then to the change in wettability, it constitutes a complete "adsorption - film formation - inhibition of wettability" action pathway. This law not only reveals the dual attributes of the gas film as a physical barrier and energy regulation carrier, deepening the understanding of the behavior of the coal-water interface in the gas environment, but also provides a quantitative design theoretical basis for optimizing gas components to regulate the wettability of the coal body and improving the efficiency of coal seam gas extraction.

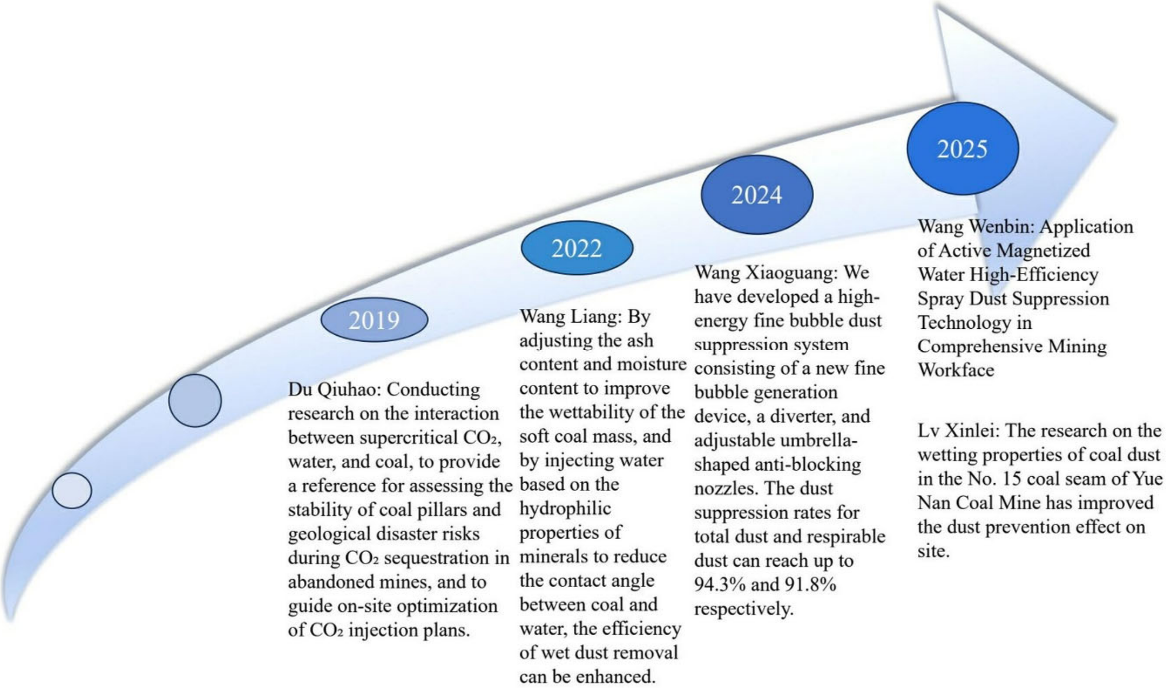
3. Exploration and Prospects of Field Applications Based on Wetting-Property Control

As theoretical research continues to deepen, the related achievements in coal wetting property control have demonstrated broad application prospects in actual engineering scenarios rich in gas. These practices are not merely the simple application of theoretical models, but rather the in-depth verification and precise control of the dominant wetting mechanism under the complex conditions of coexistence of gas, coal, and water. Their applications have run through multiple key areas ranging from mine safety to resource extraction.

In the core safety field of mine dust prevention, wetting property control technology directly confronts the challenge of water repellency caused by gas adsorption on coal dust, and has developed diversified solutions. On one hand, by enhancing the inherent hydrophilicity of the coal body to actively counteract the effect of gas adsorption, for example, Lu Xinlei [40] optimized the water injection process by measuring the contact angle of coal dust in the underground gas environment, reducing the dust concentration by more than 20%; in 2022, Wang Liang [41] in the research introduced the "gas wetting inversion" technology to solve the "water lock" problem in coal seam gas extraction, confirming that this technology can effectively reduce liquid phase retention and enhance gas desorption, opening up a new path for efficient coal seam gas development. Wang Xiaoguang et al. [42] developed a high-energy fine bubble dust suppression system consisting of a new fine bubble generating device, a splitter, and adjustable umbrella-shaped anti-blockage nozzles, and through on-site application, it was found that it could effectively resist the reverse wind of the tunneling head and fluctuations in water and air parameters, achieving a dust suppression rate of over 94% in the environment with gas coexistence; Wang Wenbin [7] studied the active magnetized water high-efficiency spray technology, which through improving the performance of the water-based medium, constructed a wider fog field with greater stability and penetration in the gas-air atmosphere, further strengthening the dust suppression effect.

In the field of resource extraction and storage, wetting property regulation also plays a crucial role. The research by Du Qiuhao et al. [43] revealed that the interaction between supercritical CO_2, water, and coal weakens the physical and mechanical properties of the coal body. This finding indicates that in the field application of CO_2 injection to displace methane in coal seams, while CO_2 competes for adsorption and replacement of methane, its plasticization and damage effects on the coal body structure pose potential risks to the safety of storage. Therefore, this research provides key guidance for on-site practice. When implementing CO_2 storage, the weakening of coal mechanical properties must be evaluated as a core risk factor, which directly relates to the accurate judgment of the long-term stability of the reserved coal pillars and the safety of storage.

Furthermore, the optimization of efficient chemical agents for the gas environment has become a frontier direction for precise control of wetting properties. The research by Shi Hanfeng et al. [44] showed that surface active agents such as CAB-35 and SDBS have specific wetting effects on different coal samples. This provides a scientific selection basis for dust prevention injection or fracturing enhancement in gas-containing coal seams. By optimizing and selecting more cost-effective agents such as CAB-35, the operational efficiency and economy in complex gas atmospheres can be significantly improved. In 2025, Yue Jiwei et al. [45] established a complete theoretical prediction and application framework starting from the essence of hydrophilic groups, from microscopic electrostatic potential to macroscopic interfacial energy to on-site wetting efficiency. Their core contribution lies in proposing the screening principle of selecting the optimal hydrophilic group of dodecyl-type surface active agents as sulfonic acid groups, and laying a microscopic theoretical foundation and screening system for on-site precise and efficient selection of surface active agents to enhance the water injection effect in gas-containing coal seams.



Du Qiuhao: Conducting research on the interaction between supercritical CO_2, water, and coal, to provide a reference for assessing the stability of coal pillars and geological disaster risks during CO_2 sequestration in abandoned mines, and to guide on-site optimization of CO_2 injection plans.

Wang Liang: By adjusting the ash content and moisture content to improve the wettability of the soft coal mass, and by injecting water based on the hydrophilic properties of minerals to reduce the contact angle between coal and water, the efficiency of wet dust removal can be enhanced.

Wang Xiaoguang: We have developed a high-energy fine bubble dust suppression system consisting of a new fine bubble generation device, a diverter, and adjustable umbrella-shaped anti-blocking nozzles. The dust suppression rates for total dust and respirable dust can reach up to 94.3% and 91.8% respectively.

Wang Wenbin: Application of Active Magnetized Water High-Efficiency Spray Dust Suppression Technology in Comprehensive Mining Workface

Lv Xinlei: The research on the wetting properties of coal dust in the No. 15 coal seam of Yue Nan Coal Mine has improved the dust prevention effect on site.

Figure 5. Advances in the Practical Application of Theories

Overall, the theoretical achievements related to the contact characteristics of coal and water in the gas environment have been applied in the coal mine field to a certain extent. From the existing practice, these achievements have achieved remarkable results by regulating the contact angle between coal and water and wetting properties in the fields of dust prevention, gas development, coal slime flotation, and disaster control. The application effects are outstanding.

4. Existing Problems and Deficiencies

At present, the research on coal-water-gas interface behavior in gas atmosphere still faces the following key challenges:

At the mechanism level, the competitive adsorption kinetics of multi-component gas such as $CH_4/CO_2/N_2$ on coal matrix surface and its quantitative influence on interface properties are not clear. Especially in the gas adsorption phase, the formation mechanism, stability of microscopic gas film and its leading role in wettability lack molecular-level experimental evidence and theoretical explanation.

At the technical method level, the existing experimental system is difficult to accurately reproduce the thermal-mechanical-flow multi-field coupling environment in underground gas drainage or sequestration process. Conventional characterization technologies are limited by spatial-temporal resolution and cannot realize the dynamic behavior capture of gas-water-coal three-phase interface in nanopores, leading to significant scale effect between laboratory data and engineering practice.

At the engineering application level, the above bottlenecks directly restrict the field regulation effect. On the one hand, there is a lack of multi-physical field model coupling gas competitive adsorption and wettability evolution, making it difficult to accurately predict the interface behavior in water injection efficiency enhancement or CO_2 sequestration process; on the other hand, there is an inherent contradiction between the goal of enhancing gas displacement through wettability regulation in engineering and the "water lock effect" caused by capillary action, and the existing technical paths are difficult to achieve synergistic resolution. In addition, the economy of technical solutions and coal permeability damage under high-pressure gas environment are also key factors restricting field application.

5. Conclusion

Coal wettability research is a core scientific problem running through many engineering fields such as efficient coalbed methane development, mine disaster prevention and CO_2 geological sequestration. This paper systematically sorts out the synergistic regulation mechanism of coal physical and chemical properties (coal rank, pore structure, minerals, surface functional groups) and external environment (gas adsorption, temperature, pressure) on coal-water contact characteristics, clarifying that gas competitive adsorption and gas film formation are the key to dynamic reversal of wettability. Moreover, current research has achieved remarkable results in field applications such as dust control and permeability increase and production increase, confirming its profound theoretical value and practical potential.

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