The main controlling factors of coal seam injection heat enhanced extraction technology

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Abstract. In order to improve the gas extraction rate in low permeability coal seam, the coal injection thermal theory was proposed. Coal seam heat injection technology is still at the stage of theoretical and laboratory research. Thermal coal injection process is a very complex multi-physics coupling problem, involving factors such as temperature, humidity, pressure and other factors on the effect of heat injection. According to the research results of seepage mechanics, heat transfer, rock mechanics and predecessors, the main controlling factors of the coal seam heat injection process are analyzed in terms of gas adsorption, desorption and coal seam permeability, and a multi-field coupling model for coal seam heat injection is analyzed and the solution of the above provides research ideas.

1. Project overview
China is rich in coal seam gas resources. Although the gas drainage technology is constantly improving and developing, the gas drainage effect is greatly limited due to the low permeability of coal seam in China [1-2]. Using the method of thermal oil displacement for reference, scholars put forward the idea of coal seam heat injection to enhance gas drainage, which will gradually become a new type of gas drainage technology. Coal seam heat injection is to inject superheated steam into the coal seam to increase the temperature of the coal body, so as to quickly desorb the gas in the form of adsorption in the coal body into a free state, and improve the permeability of the coal seam and the gas migration characteristics. The theory of coal seam heat injection involves seepage mechanics, heat transfer, rock mechanics and other disciplines. The process of coal seam heat injection includes the influence of temperature, humidity, pressure, coal seam elastic modulus and other factors. The effect of coal seam heat injection reflects the coupling effect of multiple physical fields. At present, the coal seam heat injection technology is still in the stage of theoretical and laboratory research. The analysis of the main control factors affecting the effect of coal seam heat injection is conducive to the construction of multi physical field coupling model of coal seam heat injection, which lays a foundation for further mastering the heat injection parameters and developing heat injection equipment.
2. Determination of main control factors

The coal seam is composed of solid, liquid and gas. The solid medium determines the pore and fracture structure of coal, and also affects the adsorption, desorption and permeability of coal. The liquid medium includes water and irreducible water in microcracks. The gas medium is mainly methane gas. In order to facilitate the analysis and study of coal seam and gas flow law, many geometric models of coal seam have been established by predecessors. Most people regard coal as a typical pore fracture dual medium structure. Among many coal seam geometric models, Warren root model is the most typical [3], as shown in Figure 1. Based on Warren root model, gas production goes through three processes: first, gas is desorbed from the matrix block of the model cube in the adsorption state to the free state; then, gas diffuses to the fracture system surrounded by the matrix block; finally, gas is produced by Darcy seepage in the fracture system [4]. Therefore, to improve the gas drainage rate, it is necessary to analyze from two aspects of promoting adsorption gas desorption and improving coal seam permeability, and the coal seam heat injection is to achieve the purpose of enhanced drainage from the above two aspects. In the process of coal seam heat injection, temperature, humidity, gas pressure and other main control factors will affect the gas adsorption, desorption and coal seam permeability, and ultimately determine the effect of coal seam heat injection to enhance drainage. Therefore, it is necessary to analyze these main controlling factors.

![Warren-root Model](image)

Figure 1. Warren-root Model

3. Main controlling factors of gas adsorption and desorption

The structure of coal determines that it has a large specific surface area. The stress of surface molecules and internal molecules of gas bearing coal pore system is different, forming surface potential energy, increasing the concentration of gas molecules in coal pore wall, forming adsorption phenomenon [5]. Most researchers believe that the adsorption of coal seam to gas belongs to physical adsorption, and based on different assumptions, many adsorption theoretical models under isothermal adsorption conditions are proposed. For example, Langmuir's monolayer localization adsorption model in 1918, Brunauer, emmern and teller's multilayer adsorption model in 1938, rubinin and radushkevich's adsorption potential theoretical model in 1947. However, because the temperature and moisture of coal are constantly changing in the process of coal seam heat injection, it is necessary to consider the gas adsorption model under the condition of variable temperature and moisture.

Liang Bing [6] and Yang Xinle [7] believe that with the increase of coal temperature, the gas adsorption capacity of coal gradually decreases and the gas desorption capacity increases. Zhao Dong [8] thinks that the desorption amount of coal gas increases in a "s" shape curve with the increase of temperature. Zhang Xiang [9] obtained the relationship between temperature and Langmuir adsorption constant. Zhang Zhancun [10] thinks that with the increase of water content in coal, the amount of gas adsorbed by coal decreases obviously for coal samples with different metamorphic degrees. In a word, the law of gas adsorption and desorption considering temperature and moisture conditions has been obtained through a large number of experiments. Based on the Langmuir adsorption model, the representative theoretical model of gas adsorption is [11]:
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\[ C_a = \frac{abcP\rho_n}{1+bP} \times \exp \left[ -\frac{c_2}{1+c_1P} (T_{we} + T - T_i) \right] \]

Where: \( a \) is the ultimate adsorption capacity of coal, kg/m\(^3\); \( b \) is the Langmuir pressure parameter for coal, MPa\(^{-1}\); \( P \) is the gas pressure, MPa; \( \rho_n \) is the gas density under standard atmospheric pressure, kg/m\(^3\); \( c_1 \) is the pressure coefficient, MPa\(^{-1}\); \( c_2 \) is the temperature coefficient, K\(^{-1}\); \( T_{we} \) is the absolute temperature in the state of free stress, K; \( T \) is the coal seam temperature, K; \( T_i \) is gas desorption, adsorption laboratory temperature, K; \( A \) is the ash content in coal; \( W \) is the moisture in coal; \( \rho_c \) is the density of coal, kg/m\(^3\); \( C_a \) is the gas content absorbed by unit volume of coal.

It can be seen from formula (1) that the gas content per unit volume of coal is related to the temperature of coal, moisture in coal, gas pressure and other factors. With the increase of coal temperature and water content, the amount of gas adsorption decreases and the amount of gas desorption increases. This is because the gas adsorption is an exothermic process. With the increase of coal temperature, the adsorption desorption balance of adsorbed gas is broken, the kinetic energy of adsorbed gas molecules increases, and the adsorption desorption balance is conducive to the desorption process, resulting in the decrease of gas adsorption capacity [7]; when the water content in coal increases, there is competitive adsorption between the water content in pores and gas, which makes the gas adsorption capacity decrease [5]. It can be seen that coal temperature and moisture are the main factors affecting coal seam gas adsorption and desorption.

4. Main controlling factors affecting coal seam permeability

The size of coal seam permeability determines the difficulty of gas seepage, and it is also an important factor to determine the drainage effect. Coal pores determine the storage space of gas, fractures determine the migration path of gas, and coal seam pore fracture system determines the permeability of coal seam. In the process of coal seam heat injection, the permeability of coal seam changes dynamically, and the factors affecting its change are very complex. Predecessors have done a lot of experimental and theoretical research on coal pore fracture system and its permeability. The most common experimental method is to use mercury injection method and electronic scanning microscope observation method to analyze the morphological characteristics of coal pore fracture, and use triaxial permeability meter to analyze the law of coal seam gas seepage. In theory, there are many research results on coal porosity and permeability. For example, Seidle huit model [12], Palmer mansoori model [13], Shi durucan model [14], Cui Bustin model [15] all describe the change model of porosity and permeability of coal under the influence of various factors based on the assumption of single pore medium, but ignore the coal fracture rate, which is inconsistent with the real situation.

Figure 2. Coal pore fracture deformation diagram based on Warren root model
Based on the Warren-Root model, a micro-element matrix block is taken out as the research object, as shown in Figure 2. The solid in the middle of the figure is a coal matrix block, surrounded by half a unit of cracks, the solid line is the state before deformation, and the dashed line is the state after deformation. According to theories of elastic mechanics and seepage mechanics, the strain of coal under the influence of various factors is analyzed from a microscopic point of view to obtain a mathematical model of coal seam pore-fracture system permeability [16]. which is:

\[
\frac{k}{k_{0}} = \left[ 1 - \frac{\alpha}{\phi_{0}K} \left( \frac{h_{0}}{aK_{f}} + 1 \right) \frac{\epsilon_{f}P_{f}(p_{m} - p_{0})}{(p_{L} + P_{m})(p_{L} + p_{0})(1 + \chi \cdot W)} - \epsilon_{v} \right]^{\frac{3}{2}}
\]

Where: \( k \) is the coal pore permeability, Darcy (m²); \( k_{0} \) is the initial coal pore permeability, Darcy (m²); \( k_{f} \) is the coal fissure permeability, Darcy (m²); \( k_{0} \) is the initial coal fissure permeability Rate, Darcy (m²); \( \alpha \) is the Biot coefficient; \( a \) is the opening degree of the coal matrix block; \( b_{0} \) is the initial opening degree of the coal fissure; \( K \) is the bulk modulus of the matrix block, GPa; \( K_{f} \) is the equivalent bulk modulus of the fissure, GPa; \( \phi_{0} \) is the initial coal porosity; \( \phi_{0} \) is the initial coal fracture rate; \( \epsilon_{L} \) is the Langmuir volume strain; \( P_{L} \) is the Langmuir pressure constant; \( P_{m} \) is the actual pore pressure in the coal matrix block, Pa; \( P_{0} \) is the initial pressure of the pore, Pa; \( \epsilon_{v} \) is the coal volume Strain; \( \chi \) is the humidity effect coefficient; \( W \) is the percentage of moisture in the coal. It can be seen from formula (2) that the permeability of the coal pore-fracture system is related to factors such as gas pressure, coal moisture, and coal mechanical properties. During the process of coal seam heat injection, the temperature of the coal body is constantly changing, and the temperature effect is ignored in this model. If the effect of temperature is added, the mathematical model of coal pore-fracture system permeability becomes:

\[
\frac{k}{k_{0}} = \left[ 1 - \frac{\alpha}{\phi_{0}K} \left( \frac{h_{0}}{aK_{f}} + 1 \right) \frac{\epsilon_{f}P_{f}(p_{m} - p_{0})}{(p_{L} + P_{m})(p_{L} + p_{0})(1 + \chi \cdot W)} - \epsilon_{v} \right]^{\frac{3}{2}}
\]

Where: \( \alpha_{s} \) is the thermal expansion coefficient, K⁻¹; \( \Delta T \) is the degree of coal temperature change, K; the physical meanings of other parameters are as described in formula (2). Formula (3) reflects that the coal pore-fracture permeability will change with the changes of coal temperature, moisture, pore pressure, gas adsorption and other factors.

5. Conclusion
Based on the Warren-Root geometric model and the Langmuir gas adsorption model, the coal seam gas adsorption, desorption and permeability change are analyzed from a microscopic perspective, and the main control factors of coal seam heat injection enhanced drainage are summarized. A coal-body gas adsorption model and a coal-body pore-fracture permeability change model under the influence of main control factors are established. The two models are the key coupling factors of the coal seam heat injection multiphysics coupling model, which are conducive to the analysis and solution of multiphysics
problems, and are also important factors for forming related processes and determining process parameters.

Acknowledgments
This work was financially supported by the Shanxi Province Science and Technology Major Special Project: Coal and CBM Co-production Theory and Key Technology System and Demonstration Project (No. 20201102001), Science and Technology Project of Chongqing Jiulongpo District (2020-02-008-Y), National Natural Science Foundation of China (51974358).

References
[1] Liu Jia, Li Na, Liu Yinghong, et al. Quasi stable evaluation method of coal reservoir permeability[J]. Science technology and Engineering, 2020, 20(36): 14895-14901.
[2] Wang Kuijun, Zhang Xinghua. Development status and prospects of coal mine gas drainage technology in China[J]. China Coal Bed Methane, 2006, 3(1): 13-16.
[3] Zhang Liping. Research on the mechanism and application of heat-fluid-solid coupling of low-permeability coalbed methane mining[D]. Xuzhou: China University of Mining and Technology, 2011.
[4] Yang Xinle. Research on the mechanism of low-permeability coalbed methane heat injection to increase production[D]. Fuxin: Liaoning Technical University, 2009.
[5] Zhang Xiaodong, Qin Yong, Sang Shuxun, et al. Research status and prospects of coal reservoir adsorption characteristics[J]. China Coal Geology, 2005, 17(1): 16-29.
[6] Liang Bing. Experimental study on the influence of temperature on coal gas adsorption performance[J]. Journal of Heilongjiang Institute of Mining and Technology, 2000, 10(1): 20-22.
[7] Yang Xinle, Zhang Yongli, Li Chengquan, et al. Experimental study on coalbed methane desorption seepage law under the influence of temperature[J]. Chinese Journal of Geotechnical Engineering, 2008, 30(12): 1811-1814.
[8] Zhao Dong. Research on the adsorption and desorption mechanism of coal gas under the coupled action of water and heat[D]. Taiyuan: Taiyuan University of Technology, 2012.
[9] Zhang Xiang, Tao Yunqi. Experimental study on the isotherm adsorption of coal to gas under different temperature conditions[J]. Coal Engineering, 2011, 4:87-89.
[10] Zhang Zhancun, Ma Piliang. Experimental study on the influence of moisture on gas adsorption characteristics of different coals[J]. Journal of China Coal Society, 2008, 33(2): 144-147.
[11] Li Yong. Study on structural evolution and dynamic desorption of coal driven by high temperature[D]. Xuzhou: China University of Mining and Technology, 2020.
[12] Seidle, J.P. and Huitt, L.G. Experimental measurement of coal matrix shrinkage due to gas desorption and implications for cleat permeability increases [C]. Paper SPE 30010, presented at the 1995 International Meeting on Petroleum Engineering, Beijing, China (14-17 November 1995).
[13] Palmer, I. and Mansoori, J. How permeability depends on stress and pore pressure in coalbeds: a new model [C]. Paper SPE 52607, SPE Reservoir Evaluation & Engineering(December, 1998): 539-544.
[14] Shi JQ, Durucan S. Changes in permeability of coalbeds during primary recovery-part 1: model formulation and analysis [C]. Paper 0341 proc. 2003 International Coalbed Methane Symposium, University of Alabama, Tuscaloosa, Alabama (May).
[15] Cui X, Bustin RM. Volumetric strain associated with methane desorption and its impact on coalbed gas production from deep coal seams [C]. AAPG Bull, 2005, 89:1181-1202.
[16] Wu Yu. Research on dual pore mechanics effects of carbon dioxide storage in coal seams[D]. Xuzhou: China University of Mining and Technology, 2010.