Advances in Geo-Energy Research

Vol. 15, No. 1, p. 87-90, 2025

Perspective

Multi-field coupled mathematical modeling and numerical simulation technique of gas transport in deep coal seams

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Keywords:

Coalbed gas
deep coal seams
multi-field
fractal theory
discrete fracture network

Cited as:

Wang, Q., Ji, M., Liu, G., Fan, S. Multi-field coupled mathematical modeling and numerical simulation technique of gas transport in deep coal seams. Advances in Geo-Energy Research, 2025, 15(1): 87-90. https://doi.org/10.46690/ager.2025.01.09

Abstract:

Coalbed gas production contributes to energy diversification and effectively mitigates the risk of mine gas outbursts. However, the complexity and nonlinear characteristics of multi-field coupled gas migration in deep coal seams pose significant challenges that traditional prediction and control methods struggle to address. This paper explores the effects of coupled multi-physics fields on gas migration and reviews a numerical simulation method that integrates fractal theory with discrete fracture network modeling, aiming to overcome the limitations of conventional models in capturing the interactions among seepage, heat transfer, stress distribution, and gas adsorption/desorption. The study highlights the interactions between fractures and pores, as well as the coupling effects between fluids flow, heat transfer, and solid mechanics. It further presents a more accurate prediction method to enhance the simulation accuracy of gas migration in deep coal seams.

1. Introduction

Gas extraction from deep coal seams plays an important role in both energy production and mine safety. Coalbed gas extraction provides a viable alternative to conventional energy sources, contributing to energy diversification and reducing coal mine gas outburst. However, due to the complexity of the gas migration in deep coal seams, traditional prediction and control methods cannot address the unique challenges of deep coal seams.

Gas migration in deep coal seams is influenced by a variety of physical processes, including gas adsorption, desorption, diffusion and fracture networks. These processes are influenced by the interplay of temperature changes, pressure changes and mechanical deformation within the coal matrix, creating a multi-field environment in which simple mathematical models cannot fully understand or predict gas transport behavior (Whitelaw et al., 2019). Therefore, integration of multi-field coupled models is critical for accurate prediction and optimization of gas transport. Traditional models typically focus on isolated factors, such as fracture flow or coal matrix adsorption, and fail to capture complex interactions. Multi-field coupled models combine mechanical, hydraulic, and thermal processes to provide a more comprehensive approach to understanding the prediction and control of gas migration and transport (Ge et al., 2020, Wang et al., 2021).

Despite advances in multi-field coupled modeling and numerical simulation, several challenges remain. Irregular fracture networks in coal seams make it difficult to predict gas migration on a larger scale, and the multiscale nature of gas migration complicates modeling. In addition, uncertainties in the nature of the coal seam (e.g., porosity and permeability

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Yandy Scientific Press
2207-9963
Received November 25, 2024; revised December 14, 2024; accepted December 22, 2024; available online December 25, 2024.

heterogeneity) pose additional challenges to the accuracy of the model.

For the application of multi-field coupled modeling and numerical simulation in coalbed gas mining, this perspective summarizes the key factors affecting gas transport, including pore-scale effects as well as the influence of stress distribution, high temperature, and strong adsorption-desorption properties. In addition, a fully coupled fractal permeability model is summarized to further elucidate the nonlinear gas transport mechanism under the influence of macro- and microscale multiscale and multi-factor coupling (Fig. 1).

2. Mathematical modeling of flow in deep coalbed media

By considering different perspectives on Coalbed media, gas flow models in coal seams can be categorized into three types: equivalent continuous media models, fracture network models (i.e., dual media models) that integrate the characteristics of both (Isaev, 1971; Wilson and Witherspoon, 1974; Hsieh et al., 1985; Abushaikha and Gosselin, 2008).

The equivalent continuous media model treats the coal body as a continuous medium, with permeable fluid flowing uniformly throughout the region. The equivalent continuous media model is computationally simple and efficient, making it suitable for situations where fracture density is low and the rock mass behaves homogeneously. However, its inability to accurately capture the role of fractures in fluid flow limits its applicability in fractured rock masses.

The fracture network model, in contrast, confines fluid flow to the fracture network, accurately reflecting the complex interactions between fractures and fluids. This model is well-suited for fractured rock masses, offering high fidelity and accuracy. However, it becomes computationally challenging when the fracture network is complex, requiring significant computational resources.

The dual-media model combines the advantages of both the equivalent continuous media and fracture network models. It assumes that fractures primarily facilitate fluid conduction, while the pore spaces are responsible for fluid storage. Fluid mass is exchanged through the fracture surfaces, ensuring mass conservation. The dual-media mode comprehensively accounts for the interactions between fractures and pores, making it widely applied in engineering practice. However, the dual-media model is relatively complex, requiring more input parameters. Furthermore, in some real-world applications, simplifying assumptions about the interactions between fractures and pores may lead to incomplete modeling of the flow characteristics.

3. Mathematical model of nonlinear migration of gas in deep coal seam

The nonlinear migration process of multi-field coupled gas in deep coal seams involves the coupling, including gas adsorption and desorption, diffusion, fissure network flow, and fluids flow and heat transfer effects in low-permeability media. In deep coal seams, high-temperature and high-pressure conditions cause gas desorption to exhibit strong nonlinear behavior, introducing significant uncertainty in the desorption rate. The adsorption-desorption behavior of gas is highly sensitive to variations in temperature and pressure, further complicating the modeling of gas migration (Hao et al., 2021). Therefore, a comprehensive model that integrates thermal effects, gas desorption dynamics, and permeability changes is essential for improving the accuracy of gas migration predictions in deep coal seams.

The distribution and geometry of the coal seam fracture network, as the primary channel for gas flow, directly influence both the path and rate of gas migration. While the fracture network model provides a more accurate description of the gas migration process, the randomness and irregularity of fractures in the coal seam increase the model's complexity (Blokhina et al., 1959). To address this issue, fractal theory has been incorporated into coal seam gas migration modeling. Fractal theory posits that the morphology of rock fractures is self-similar and irregular, with the fracture network distribution describable through the fractal dimension, offering an effective mathematical tool for modeling complex fracture networks (Zhu et al., 2020). By applying fractal theory, the complexity of the fracture network in coal seams can be more accurately represented, enhancing the simulation accuracy of gas migration.

The migration behavior of low-permeability coal seams exhibits significant nonlinear characteristics, particularly in the migration of gas through the fracture and pore systems. During mining, the porosity, fracture density, and their evolution are critical to gas migration. In low-permeability coal seams, gas flow is not only constrained by the physical properties of the coal body but also influenced by changes in porosity and the reconfiguration of the fracture network induced by mining (Abushaikha and Gosselin, 2008). By incorporating fractal theory, the model can quantify porosity changes and fracture network reconfiguration through the fractal dimension, enabling a more accurate simulation of the nonlinear behavior of gas migration (Liu et al., 2021).

Future research should focus on the integration of thermal effect, fluid mechanics, mechanical deformation and other physical fields, and further incorporating fractal theory to develop more accurate mathematical models, providing valuable theoretical support for deep coal seam gas mining.

4. Numerical simulation of multi-field coupling

The coupled thermal-fluid-solid numerical simulation has become a key tool for studying gas migration in deep coal seams, enabling the analysis of coal seam gas flow patterns and the complex feedback effects during mining. This method combines the finite element method, finite difference method, and finite volume method to solve equations involving interactions among multiple physical fields, such as temperature, pressure, stress, and permeability. Finite element method simultaneously solves the temperature, pressure, and stress fields within a unified computational framework, facilitating joint simulations of gas flow, desorption, and coal seam deformation. Finite difference method provides a simple and efficient numerical solution, making it suitable for modeling temper-

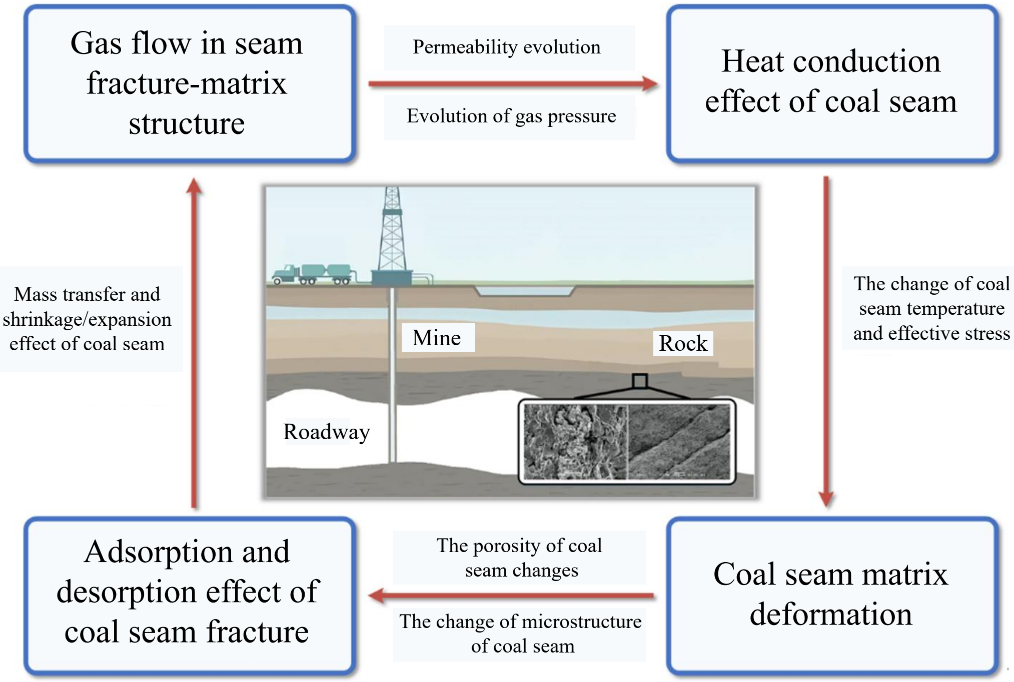

Fig. 1. Mathematical modeling of gas transport in deep coal seams.

ature, pressure, and stress variations in regular geometries. Finite volume method is particularly advantageous in fluid dynamics, especially for multiphase flow and non-uniform media, as it ensures mass conservation and is effective for modeling coupled fracture flow and heat transfer.

Fractal theory has been introduced into the coupled thermal-fluid-solid numerical simulation as a tool for describing complex fracture networks. It provides a mathematical framework to quantify the complexity of fracture networks by capturing the geometric features of fractures through self-similarity and irregularity. By integrating fractal theory, the model can more accurately represent the evolution of fractures in coal seams and their effects on gas migration, especially in low-permeability seams, thereby enhancing simulations of gas flow and diffusion.

5. Numerical simulation of multi-field coupling

The nonlinear migration of deep coalbed gas involves the complex coupling of several physical fields. While various numerical simulation methods and models have been proposed and applied to coalbed gas mining, significant challenges remain.

Complexity of the fracture network and multiscale heterogeneity of the coal seam: Although methods such as fractal theory, discrete fracture network models, and digital core reconstruction provide partial descriptions of the coal seam microstructure, they still have limitations in terms of adaptability to complex coal seam environments.

Matrix complexity in the nonlinear migration process of natural gas: Current mathematical models often rely on simplified assumptions to address nonlinear effects, failing to fully account for the complexity of the underlying physical processes.

Multi-physics field coupling and computational efficiency: Coupled thermal-fluid-solid numerical simulations typically involve large-scale computations, especially in the high-stress, high-permeability, and heterogeneous environments of deep coal seams, where computational costs and time are substantial. While existing numerical simulation software excels in certain areas, it still suffers from inefficiencies when applied to complex coalbed methane mining problems.

6. Conclusions

The nonlinear migration of gas in deep coal seams involves complex interactions among various physical processes, such as fluids flow, heat transfer, stress distribution, and gas adsorption/desorption.This paper reviews a multi-field coupled numerical simulation method that integrates fractal theory with fracture network modeling. By considering the interactions between fractures and pores, along with the coupled effects of fluids flow, heat transfer, and solid mechanics, this approach provides a more accurate prediction of gas migration behavior in deep coal seams.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities (No. 2023ZDYQ11006),the National Key Research and Development Program of China (No. 2022YFE0128300), and the Open Foundation of Shale Gas Evaluation and Exploitation Key Laboratory of Sichuan Province(No. YSK2023003).

Conflict of interest

The authors declare no competing interest.

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