Numerical Simulation of Coal Seam Floor Under Multi-field Coupling

Hao Li and Chunhui Yang

Abstract This article presents a THM (Thermal–Hydrological–Mechanical) coupling model for the temperature field, seepage field, and stress field of rock masses. The study investigates the inherent effects of various structural rock masses when subjected to the coupling of tectonic stress field, rock mass temperature field, and groundwater seepage field. Firstly, the connected THM model's governing equation was formulated by integrating the equations related to solid deformation, seepage control differential, mechanics, and heat transfer. Secondly, the coupling model is built by setting boundary conditions. Finally, the model was numerically simulated using COMSOL Multiphysics. The results showed that under the coupling effect of stress seepage temperature, there is almost no effect on the geothermal in the promoting process of the production, whereas the seepage field has a great influence on the temperature distribution, and the temperature contour will move toward the seepage velocity. The faster the seepage velocity is, the greater the influence on the geothermal gradient is, and the more obvious the influence on the temperature distribution.

Keywords floor water inrush · THM coupling model · Numerical simulation · Temperature

1 Introduction

Under the special conditions of deep rock mass, the problem of floor water inrush caused by deep engineering disturbance is a major hidden danger of coal mine safety production in China [1]. In the evolution process of water inrush disaster, mining activities form the dynamic load of surrounding rock fiber mass. The coupling induction of THM of fractured rock mass under dynamic load change is the key to the emerging of water channel in rock strata. Based on Biot's consolidation theory and

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S. Yadav et al. (eds.), *Energy Power and Automation Engineering*, Lecture Notes in Electrical Engineering 1118, https://doi.org/10.1007/978-981-99-8878-5_19

different assumptions, foreign scholars have proposed different mechanical models of THM coupling process [2]. Based on the small deformation and thermoelastic linear theory of porous materials, Chinese scholars have derived a set of relatively complete THM coupling equations [3], established a thermal-fluid–solid coupling mathematical model, and numerically solved it [4]. In the study of nonlinear seepage of fault water inrush, Zhao et al. [5] proposed a nonlinear seepage-stress coupling model. Zhang et al. [6] used COMSOL software to calculate the three-dimensional model of fluid-thermal coupling in Panxi Coal Mine, which included the parameters of monoclinic fault zone. The calculation results show that the cracks and seepage in the rock fiber mass will lead to the fluctuation of the temperature field of the rock fiber mass. Bian et al. [7] used FLAC3D numerical simulation software, from the perspective of the coupling effect of stress, displacement, seepage, and failure zone, the law of water inrush from coal seam floor under different conditions of fault morphology and confined water pressure was analyzed. Li et al. [8] conducted numerical simulation and experimental verification on the variation law of each physical field during the deformation and failure of coal and rock under load.

At present, many scholars have studied the prediction of water inrush of floor caused by coal seam mining from the view of theory, modeling, experiment, and measurement, and obtained the relevant control criteria of water inrush [9]. There are relatively few studies on the coupling of multi-field interaction in deep rock mass environment, especially the evolution pattern of temperature field under multi-field coupling conditions. Therefore, the paper will use numerical simulation software to simulate and analyze on the basis of theoretical research.

2 Governing Equations of Coupled THM Model

2.1 Fluid Solid Coupling Solid Deformation Equation

Under planar conditions, the equilibrium conditions for force expressed in tensor form are:

$$-\nabla \cdot [\sigma] = F \tag{1}$$

where $[\sigma]$ is the stress tensor; F is a force vector that includes fluid pressure gradient and other stresses.

2.2 Differential Equation for Seepage Control

According to the law of conservation of mass, the fluid flow equation is

$$\frac{\partial(\phi\rho_1)}{\partial t} + \nabla\phi\rho_1 V_1 = Q \tag{2}$$

where ϕ is the porosity of the rock mass, ρ_1 is the fluid density, t represents time, V_1 is the fluid velocity vector field, and Q is the source-sink of the fluid.

$$V_1 = -\frac{k}{\mu_1}(\nabla P - \rho_1 g) \tag{3}$$

where k is the permeability of the rock mass, μ_1 is the hydrodynamic cohesive soil viscosity, P is the interstitial pressure, and g is the gravitational acceleration.

Combining the above three equations is the stress seepage coupling control equation.

3 Model Establishment

3.1 Geometric Modeling

Simplify the model based on the actual mining geological conditions and comprehensive rock column chart of Anju Coal Mine, and only consider the rock layers within a certain range near the coal seam roof and floor that needs to be calculated. For the convenience of simulation calculation, on the basis of meeting the actual geological conditions, reasonable composite should be carried out for rock layers with similar physical properties, and treated as single rock layers [10]. Based on the actual occurrence of coal seams, the coal seam is set as a level coal seam in based model, with a strike length of 253 m, and the working face is arranged along the strike. The direction of coal seam mining is X-axis, and the gravity direction is Y-axis. The overlying strata of the coal seam are divided into three layers, with sandstone of 45 m, mudstone of 30 m, and sandstone of 15 m from top to bottom. The coal seam is 3 m long, and the lower layer of the coal seam is allocated to 4 layers, with mudstone 4.2 m, sandstone 50.3 m, mudstone 35 m, and water-bearing limestone 5.7 m from top to bottom.

3.2 Model Parameter Settings

The mechanical and physical parameters of various rock formations in the model are defined using material parameters in the software, as illustrated in Table 1. After setting up and characterizing the geometric modeling and the physical property of each rock burst, it is necessary to network the model. In order to reduce computational complexity whereas guaranteeing a certain degree of precision, the unit estimate of the lattice is chosen at the standard level.

Table 1 Material parameters of numerical simulation model

Number	Nature of ground	Density (kg/m^3)	Bulk modulus(GPa)	Shear modulus (GPa)	Permeability (m^2)	Porosity
1	Sandstone	2660	9.896	8.051	1e-14	0.05
2	Sudstone	2524	8.730	4.264	2e-14	0.12
3	Sandstone	2660	9.896	8.051	1e-14	0.05
4	Coal	1400	5.455	1.295	6e-14	0.20
5	Mudstone	2480	8.730	4.264	2e-14	0.12
6	Sandstone	2660	9.896	8.051	1e-14	0.05
7	Mudstone	2480	8.730	4.264	2e-14	0.12
8	Water-bearing Limestone	2620	10.417	5.952	1e-13	0.25

3.3 Boundary Conditions

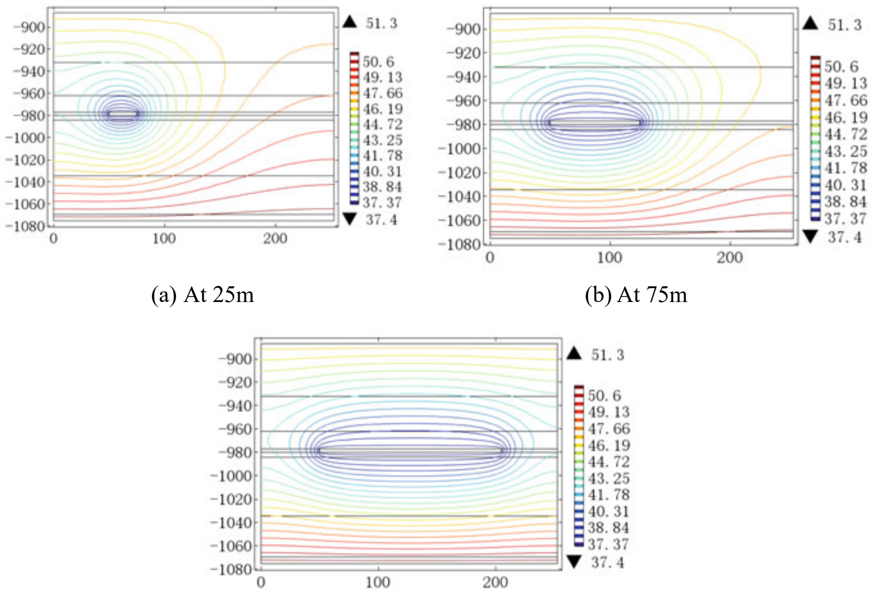
Based on the geology situation and geothermal data of Anju Coal Mine, the gravity of the overlying stratum of the coal stratum is equivalent to a boundary load of 22 MPa. The gravity effect is activated by the model's self weight in the software, and the floor and left and right sides of the model are respectively constrained by fixed and roller supports. The overall temperature of the model is set at 37 °C, with upper and lower boundary temperatures of 47.32 and 51.7 °C, respectively.

4 Numerical Calculation and Analysis

4.1 Temperature Distribution at Different Driving Distances

After calculation, the temperature distribution under different propulsion distances is obtained, as shown in Fig. 1.

As shown in Fig. 1, as the progress of mining production, the temperature field near the coal seam will be redistributed. Due to the destruction of the original rock stress state, the stress in the rock of the mining zone will be redistributed. Stress concentration will occur close to the open-cutting and working face, accompanied with the generation and development of cracks, and the continuous heat exchange process. The temperature of the top and bottom of the coal bed gradually approaches the temperature of the rock mass medium, and the heat reaches an equilibrium state within the given range, thus the distribution of temperature field in the original vertical direction gradually changed. In addition, this temperature change is only in the direction of advancement, which only occurs near the temperature near the mining site. However, in the relatively far vertical direction, the temperature of the



(a) At 25m

(b) At 75m

(c) At 155m

Fig. 1 Contour map of temperature distribution in advance of working face

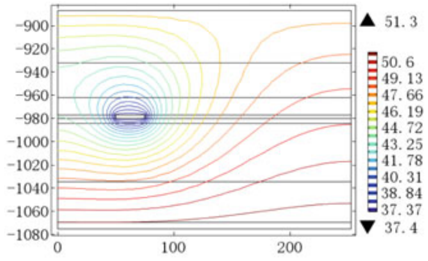
entire rock layer does not change much, which means that there is almost no effect on the temperature gradient in the promoting process of the production.

4.2 Effect of Seepage on Temperature Distribution

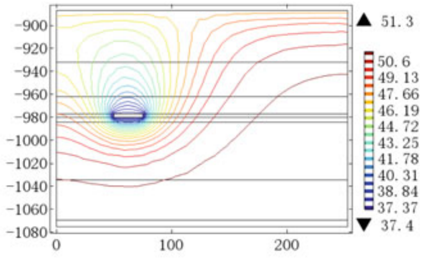
According to the research plan, in order to facilitate the study of the effect of seepage on temperature distribution, the seepage velocity is amplified. The specific plan is to enlarge the seepage velocity by 10–100 times to calculate the temperature distribution, as shown in Fig. 2.

It can be seen from Fig. 2 that with the increase of seepage velocity, the original temperature field of the embracing rock is redistributed under the influence of the seepage field with upward velocity, and the heat exchange balance zone is shifted to the direction of seepage velocity, so the isotherm is shifted upward.

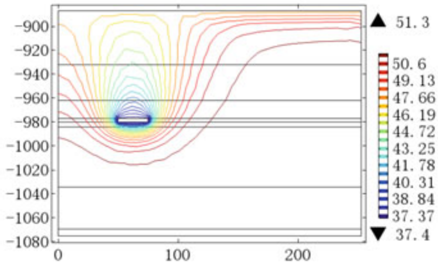
Figure 3 shows the temperature change of the coal seam floor at the same depth under the influence of seepage velocity. It is evident from the figure that when the seepage velocity is amplified by 10 times and by 100 times, the maximum temperature difference can reach 3 °C.



(a) At 10x



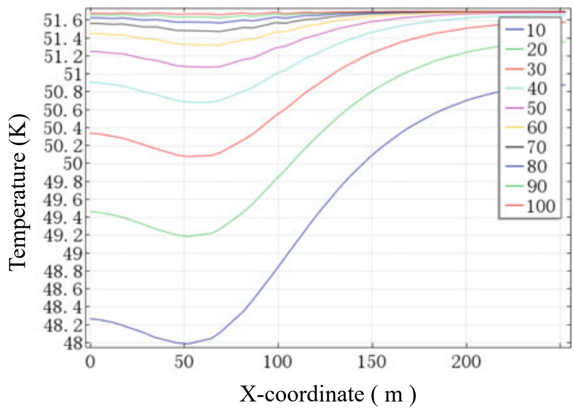
(b) At 50x



(c) At 100x

Fig. 2 Isogram of temperature distribution at different magnification of seepage velocity

Fig. 3 Temperature distribution curve at 50 m from the upper boundary of the direct bottom under different seepage velocities



5 Conclusion

(1) Under the coupling effect of stress seepage temperature, different footage only affects the temperature distribution near the stope and has little effect on the geothermal gradient in the promoting process of the production.

(2) The seepage field has a great influence on the temperature distribution. The seepage field will affect the geothermal gradient, and the heat exchange balance zone will shift to the seepage velocity direction, which will eventually cause the temperature contour to move within the heading of seepage velocity. The faster the seepage velocity is, the greater the influence on the geothermal gradient is, and the more obvious the influence on the temperature distribution is. Therefore, the seepage field is the main factor affecting the geothermal distribution.

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