Coal Seam Heat Injection Multi-physics Coupling Model with Humidity Effects

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Abstract: Coal seam heat injection is a new way of strengthening drainage gas. In the thermal process in coal seam, steam humidity increases will affect the extraction of coal seam gas. In order to grasp the effect of humidity on the steam injection thermal process, on the basis of previous research and heat transfer, fluid mechanics, theory of elasticity, adding the effects of humidity, the thermal coal injection multi-physics coupling model with humidity effects is established. The model is helpful for future numerical analysis and related laboratory experiments.

1. Introduction

Gas is a kind of gas in coal seam. Enhanced extraction of coal seam gas can not only prevent coal mine gas disasters, but also can be used as clean gas. The permeability of coal seams in China is generally low, so the effect of gas extraction is greatly affected[1-2]. The performance of coal gas desorption is generally enhanced with the increase of temperature, which has obvious promoting effect on coal gas desorption. The influence of temperature on coal permeability is more complex, and the reaction of raw coal and briquette permeability to temperature is different. The reaction of coal permeability to temperature is also different for different ranks of coal, which is mainly reflected in the Thermal-Fluid-solid coupling effect of coal. In this field, some studies have been carried out [3-5], and the corresponding governing equations have been proposed. Therefore, on the basis of previous studies, this paper is based on the theory of elasticity and heat transfer, the permeability change analysis model under the condition of coal seam heat injection (steam) is established to analyze the coupling effect of heat injection factors such as temperature, moisture and effective force on coal seam permeability.

2. Coal seam porosity and permeability model

The number of coal seam pore and fissure can reflect the permeability of coal seam. In the Warren-Root geometric model of coal seam [6], the micro-matrix block of coal body is taken as the research object (as shown in Fig.1). In the middle of the graph, the matrix block is coal, the surrounding cracks are half units, the solid line is pre-deformation state, and the dotted line is post-deformation state.

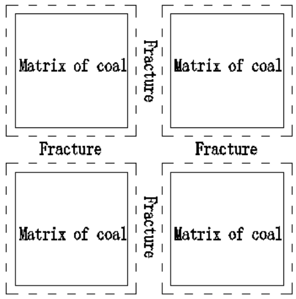

Fig.1 Coal matrix block diagram based on Warren-Root model

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In Fig.2, a is the width of coal matrix block (and a≫b), b is the width of coal fracture, d is the sum of the width of coal matrix block and fracture, △a is the opening of coal matrix block, and △b is the opening of coal fracture.

In the process of heat injection, the deformation of coal seam is mainly affected by three kinds of functions: temperature, gas adsorption and desorption, and the change of effective stress of coal seam. On the basis of literature[6], considering the effect of temperature and combining Langmuir adsorption equation, the volume deformation formula of coal matrix block can be obtained.

$$\varepsilon_m = \alpha_m \Delta T - \frac{1}{K_m}\Delta\sigma_m + \varepsilon_L\left(\frac{p_m}{p_L + p_m} - \frac{p_{m0}}{p_L + p_{m0}}\right) \tag{1}$$

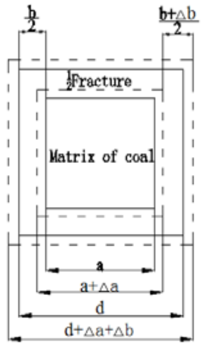

Fig.2 Schematic diagram of dual porosity media deformation of coal matrix element

In the formula (1): ε_m is the volume strain of the coal matrix block, α_m is the thermal expansion coefficient of the coal matrix block, K_m is the bulk modulus of the matrix block, $\Delta\sigma_m$ is the action force of the crack on the matrix block, ε_L is the Langmuir volume strain, p_L is the Langmuir pressure constant, p_{m0} is the initial pressure of the coal seam pore, and p_m is the actual pore pressure in the coal matrix block.

Because the adsorption of gas in coal seam fissures is not obvious, the formula of volume strain in the fissure system can be obtained by neglecting the adsorption of gas in the fissure system.

$$\varepsilon_f = -\frac{1}{K_f}\Delta\sigma_f - \frac{\alpha_m \Delta T}{3} \tag{2}$$

In the formula (2): ε_f is the volume strain of coal fissures, $\Delta\sigma_f$ is the action force of matrix blocks on fissures, $\Delta\sigma_m = \Delta\sigma_f = \Delta\sigma$, K_f is the equivalent volume modulus of fissures, $K_f = aK_n$, K_n is the stiffness of fissures.

Therefore, according to Fig. 2, the deformation formulas of coal pore and fracture can be calculated.

$$\begin{cases} \Delta d = \Delta b + \dfrac{a\varepsilon_m}{3} \\ \varepsilon = \dfrac{b}{a}\dfrac{\varepsilon_f}{3} + \dfrac{\varepsilon_m}{3} \end{cases} \tag{3}$$

In the formula (3): ε is the sum of volumetric strain of fracture and matrix block in a certain direction.

Substituting (1) and (2) into (3) can calculate the micro-element volumetric strain of coal under the influence of temperature, gas adsorption and desorption, effective stress between coal matrix and fissures, etc.

$$\varepsilon = \frac{1}{3}\left\{\frac{2}{3}\alpha_m \Delta T + \varepsilon_L\left[\frac{p_m}{p_L + p_m} - \frac{p_{m0}}{p_L + p_{m0}}\right] - \left[\frac{b}{aK_f} + \frac{1}{K_m}\right]\Delta\sigma\right\} \tag{4}$$

According to the definition of porosity of pore system in coal matrix, the formula for calculating the porosity of coal seam is as follows:

$$\phi = \frac{V_p}{V} = \frac{V_p}{V_p + V_s} \tag{5}$$

In the formula (5): V is the total volume of coal matrix, V_p is the pore volume of coal matrix, and V_s is the solid volume of coal matrix.

From the definition of volume deformation of coal matrix block and formula(1), it can be concluded that:

$$\varepsilon_m = -\frac{\Delta V}{V} = \frac{\Delta V_s}{V_s} + \frac{\Delta\phi}{1-\phi} = \alpha_m \Delta T + \frac{\varepsilon_L P_L \left(p_m - p_{m0}\right)}{\left(p_L + p_m\right)\left(p_L + p_{m0}\right)} - \frac{1}{K_m}\Delta\sigma \tag{6}$$

Assuming that pore strain of coal body is only affected by effective stress, combined with the definition of pore deformation of coal body, it can be calculated:

$$\begin{cases} \varepsilon_p = -\dfrac{\Delta V_p}{V_p} = \dfrac{\Delta V_s}{V_s} + \dfrac{\Delta\phi}{(1-\phi)\phi} = -\dfrac{1}{K_p}\Delta\sigma \\ K_p = \dfrac{\phi K_m}{\alpha} \end{cases} \tag{7}$$

In the formula(7): K_p is the bulk modulus of coal pore, α is the Biot coefficient of coal matrix.1

Combination (5), (6), (7) can be obtained:

$$\Delta\phi = -\phi\left(\varepsilon_m - \varepsilon_p\right) \tag{8}$$

Formula (8) is transformed and expanded to obtain:

$$\phi = \frac{\phi_0 - \dfrac{\alpha\Delta\sigma}{K_m}}{1 + \alpha_m \Delta T + \dfrac{\varepsilon_L P_L \left(p_m - p_{m0}\right)}{\left(p_L + p_m\right)\left(p_L + p_{m0}\right)}} \tag{9}$$

When the temperature of coal body reaches a certain value, the thermal effect of coal body will cause thermal fracture of coal body, or the volatile substances in coal body will dissipate, which will eventually lead to the increase of coal seam porosity. The temperature influence coefficient γ is introduced to express the influence of temperature to coal seam porosity when the temperature reaches a certain range.

Formula (9) can be transformed into a porosity model of coal matrix block considering the influence of temperature.

$$\phi = \frac{\phi_0 - \dfrac{\alpha\Delta\sigma}{K_m}}{1 + \alpha_m \Delta T + \dfrac{\varepsilon_L P_L \left(p_m - p_{m0}\right)}{\left(p_L + p_m\right)\left(p_L + p_{m0}\right)}} + \gamma\Delta T \tag{10}$$

By using Kotyakhov porosity and permeability model:

$$k_m = \frac{d_e^2 \phi^3}{72\left(1-\phi\right)^2} \tag{11}$$

In the formula(11): k_m is pore permeability of coal matrix block, Darcy (m^2), d_e is effective diameter of coal matrix particle, M.

Based on the relationship between porosity and permeability, the coupling model of coal seam pore permeability and physical properties of coal seam itself, coal seam temperature, gas adsorption and effective force can be calculated.

$$\frac{k_m}{k_{m0}}=\left[\frac{1}{\phi_0}\frac{\phi_0-\dfrac{\alpha\Delta\sigma}{K_m}}{1+\alpha_m\Delta T+\dfrac{\varepsilon_L P_L\left(p_m-p_{m0}\right)}{\left(p_L+p_m\right)\left(p_L+p_{m0}\right)}}+\frac{\gamma\Delta T}{\phi_0}\right]^3 \tag{12}$$

In the formula(12): k_{m0} is the initial pore permeability of coal matrix block.

3. Fracture rate and permeability model of coal seam

According to Fig. 2 and the definition of fissure rate, the calculating formula of micro-element fissure rate of coal body can be obtained.

$$\varphi=\frac{\left(a+b\right)^3-a^3}{\left(a+b\right)^3}\cong\frac{3b}{a} \tag{13}$$

$$\frac{\varphi}{\varphi_0}=1+\frac{\Delta b}{b_0} \tag{14}$$

In the formula(13)(14): φ is the micro-element fracture rate of coal, φ_0 is the initial micro-element fracture rate of coal.

According to the micro-fracture deformation of coal body, it can be concluded that:

$$\frac{\Delta b}{b_0}=\varepsilon_f=-\frac{\Delta\sigma}{K_f}-\frac{\alpha_m\Delta T}{3} \tag{15}$$

Simultaneous (14) and (15) coalbed fissure rate models can be obtained:

$$\frac{\varphi}{\varphi_0}=1+\frac{\Delta b}{b_0}=1-\frac{\Delta\sigma}{K_f}-\frac{\alpha_m\Delta T}{3} \tag{16}$$

From the relationship between coal seam fissure permeability and fissure permeability, the coupling relationship between coal seam fissure permeability and physical and mechanical properties of coal seam itself, coal seam temperature and effective stress of coal seam can be obtained.

$$\frac{k_f}{k_{f0}}=(\frac{\varphi}{\varphi_0})^3=(1-\frac{\Delta\sigma}{K_f}-\frac{\alpha_m\Delta T}{3})^3 \tag{17}$$

In the formula (17): k_f is the micro-fracture permeability of coal matrix, k_{f0} is the initial micro-fracture permeability of coal matrix.

4. Mathematical model of coal seam pore-fracture permeation under water influences

Previous studies have shown that the presence of water in coal seams will hinder the adsorption of gas in coal matrix blocks, thus affecting the adsorption deformation of coal.

The adsorption strain formula of coal seam gas under the influence of water content:

$$\varepsilon_s=\varepsilon_L\frac{p_m}{\left(p_m+p_L\right)\left(1+\chi W\right)} \tag{18}$$

In the formula (17): ε_s is the volume strain produced by adsorption, χ is the coefficient of water influence, W is the percentage of water in coal.

By introducing formula (18) into formula (10), the porosity model of coal matrix under the combined influence of temperature, moisture, effective stress and adsorption and desorption can be obtained.

$$\phi = \frac{\phi_0 - \frac{\alpha\Delta\sigma}{K_m}}{1+\alpha_m\Delta T + \varepsilon_L[\frac{p_m}{(p_L+p_m)(1+\chi W)} - \frac{p_{m0}}{(p_L+p_{m0})(1+\chi W_0)}]} + \gamma\Delta T \tag{19}$$

Combining the model functions (12) and (17) of the relationship between pore and fracture, the mathematical model of coal micro-element pore-fracture permeability under the combined effect of temperature and water shadow can be obtained.

$$\begin{cases} \frac{k_m}{k_{m0}} = \left[\frac{1}{\phi_0} \frac{\phi_0 - \frac{\alpha\Delta\sigma}{K_m}}{1+\alpha_m\Delta T + \varepsilon_L[\frac{p_m}{(p_L+p_m)(1+\chi W)} - \frac{p_{m0}}{(p_L+p_{m0})(1+\chi W_0)}]} + \frac{\gamma\Delta T}{\phi_0} \right]^3 \\ \frac{k_f}{k_{f0}} = (1 - \frac{\Delta\sigma}{K_f} - \frac{\alpha_m\Delta T}{3})^3 \end{cases} \tag{20}$$

From the model function (20), it can be seen that the permeability and temperature of coal seam, real-time moisture content of coal seam, pore pressure and other factors are closely related in the process of coal seam heat injection.

5. Coupled model of multi-physical field for coal seam heat injection

5.1 Seepage field equation

According to the principle of mass conservation, Darcy's seepage law, gas state equation and gas content equation, the influence of temperature and pressure on gas seepage during heat injection process is comprehensively considered. The seepage field equation of gas in coal seam can be described as:

$$\frac{\partial\left[\frac{\rho_n(\phi+\varphi)P}{P_n} + \frac{abcP\rho_n}{1+bP} \times \exp\left[-\frac{0.02}{1+0.07P}T\right]\right]}{\partial t} = \nabla \bullet \left(\frac{P\rho_n}{P_n}\frac{k}{\mu}\nabla P\right) \tag{21}$$

In the formula(21): k is the permeability of coal seam,m^2. μ is the absolute viscosity of gas, Pa·S. ∇P is the pressure gradient of gas, MPa/cm.

5.2 Equation of temperature field

According to the heat transfer theory, the temperature field equation of coal seam heat injection can be obtained.

$$\begin{aligned} &\left[\rho_s c_s + (\phi+\varphi)\rho_g c_g\right]\frac{\partial T}{\partial t} + \Delta T \rho_g c_g \frac{\partial(\phi+\varphi)}{\partial t} \\ &+ T\alpha_s K \frac{\partial \varepsilon_v}{\partial t} + \rho_g c_g \Delta T \nabla \bullet q_g + \nabla\cdot(k_t \nabla T) = Q_T \end{aligned} \tag{22}$$

5.3 Stress field equation

According to the constitutive equation, equilibrium differential equation and geometric equation of coal seam deformation under the influence of various factors, the thermal stress field equation of coal seam can be obtained [7].

$$\begin{aligned} &Gu_{i,kk} + \frac{G}{1-2\nu}u_{k,ki} - \alpha_s KT_{,i} - \alpha p_{,i} \\ &-K\frac{\varepsilon_L p_L}{(p+P_L)^2(1+\chi \bullet W)} p_{,i} + f_{,i} = 0 \end{aligned} \tag{23}$$

6. Conclusion

The simultaneous (20)~(23) model is a coupled multi-physical field model of coal seam heat injection. The multi-field coupling equations are coupled with each other and the corresponding conditions are added to analyze the law of gas flow, temperature change and gas pressure change in coal seam under heat injection conditions. The model establishes the coupled model of multi-physical field of coal seam heat injection. The model shows that the effect of coal seam heat injection is not only related to temperature and pressure, but also to the water content of coal seam. It improves the theory of coal seam heat injection and provides theoretical reference for the next laboratory verification and numerical analysis.

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