The Software Development for Establishing Thermal-Hydraulic-Mechanical Coupling Models of Fractured Rocks

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Abstract

In order to provide a more convenient and efficient method to establish thermal-hydraulic-mechanical coupling models for fractured rocks, a software specialized was developed by the secondary development of COMSOL Multiphysics. The software can provide advanced settings for the geometry of pores and porosity distribution. The geometry of pores and porosity distribution can be defined as random distribution or Weibull distribution. A mechanical test was carried out to the rock specimen with a single pre-existing crack inclined at 45° using the MTS815.03 electrohydraulic servo controlled rock pressure testing machine. Then the experimental results was imported into the software to build the geometric model. Results indicate that fluid stress concentration occurred in the wring crack tip, which contributes to the crack propagation. The thermal stress mainly distributed in an area formed by connecting the wring crack tips. The permeability increases with increasing rock heterogeneity and the increase of rock heterogeneity contributes the crack growth.

Keywords: THM coupling, numerical model, fractured rock, porosity distribution, secondary development

Introduction

Water inrush frequently happens in China's coal mines, which has been a major threat to mine safety production. The complexity of geological systems in deep mines including high ground temperature, high groundwater pressure, and high ground stress, has motivated researchers to consider the temperature (T), hydraulic flow (H), and mechanical deformation (M) coupling model for fault water inrush. In particular, the framework of international projects like DECOVALEX has dramatically promoted the study of the THM coupling process (Bond et al. 2017; Jing et al. 1995; Rutqvist et al. 2002; Tsang et al. 2005). Sheng (2006) proposed a mechanical model of coupled THM processes for saturated porous media, and this model was translated into a set of partial differential equations by using COMSOL. Zhu et al. (2009) proposed a THM coupling model considering rock damage. In the aspect of predicting fault water inrush, Sun et al. (2011) used high-precision microseismic monitoring techniques to monitor the continuous and dynamic failure characteristics of an inclined coal seam floor above a confined aquifer. Bai et al. (2015) established the identification criteria for monitoring and warning based on multiple field information monitoring and warning on delayed water bursting in a deep rock fault. Zhou et al. (2018) predicted the fault water inrush under the effect of mining depth, fluid pressure, fault dip, and fault length. Although a series of research on the THM coupling model have been carried out, most THM models were established by common software, instead of the software specialized for fractured rocks. In view of this, the major objective of this paper is to develop a software specialized for fractured rocks by the secondary development of COMSOL Multiphysics. The software can provide advanced settings for the geometry of pores and porosity distribution. The geometry of pores and porosity distribution can be defined as random distribution or Weibull distribution. A mechanical test was carried out to the rock specimen with a single pre-existing crack inclined at 45° using the

MTS815.03 electrohydraulic servo controlled rock pressure testing machine. Then the experimental results was imported into the software to build the geometric model.

Governing Equations for the THM Coupling Model

Water flow equation

According to previous work of the author (Liu et al. 2018), the water flow equation is the Darcy's-Brinkman-Navier–Stokes equation

$$\begin{cases} \boldsymbol{u}_d = -\dfrac{k}{\mu}(\nabla p_d - \rho \boldsymbol{g}) \\ \left(-\nabla \cdot \dfrac{\mu}{\varepsilon}\left(\nabla \boldsymbol{u}_b + (\nabla \boldsymbol{u}_b)^T\right)\right) - \left(\dfrac{\mu}{k}\boldsymbol{u}_b + \nabla p_b\right) = 0 \\ -\nabla \cdot \mu\left(\nabla \boldsymbol{u}_n + (\nabla \boldsymbol{u}_n)^T\right) + \rho \boldsymbol{u}_n \cdot \nabla \boldsymbol{u}_n - \nabla p_n = 0 \end{cases} \tag{1}$$

Where $\boldsymbol{u}_d$, $\boldsymbol{u}_b$, and $\boldsymbol{u}_n$, are the velocity vector in the confined aquifer, the fault and the stope respectively; p_d, p_b, and p_n, are the water pressure in the confined aquifer, the fault, and the stope respectively; μ is the dynamic viscosity of water (N·s·m^{-2}); k is the permeability of porous rock (m^2); p_d is the water pressure (Pa); ρ is the water density (kg·m^{-3}); $\boldsymbol{g}$ is the gravitational acceleration (m·s^{-2}); ε is the porosity.

The energy conservation equation for porous media

According to Sheng et al. (2006), the energy conservation equation for solid skeleton is

$$(1-\phi)(\rho c_{\mathrm{p}})_{\mathrm{s}} \frac{\partial T}{\partial t} = (1-\phi)\nabla(K_{\mathrm{s}} \nabla T) + (1-\phi) q_{\mathrm{s}} \tag{2}$$

Where $(\rho c_{\mathrm{p}})_{\mathrm{s}}$ is specific heat capacity of solid skeleton (J/(kg•K)); K_{s} is thermal conductivity of solid skeleton (W/(m•K)); q_{s} is heat source intensity of solid skeleton.
The energy conservation equation for fluid is

$$\phi(\rho c_{\mathrm{p}})_{\mathrm{l}} \frac{\partial T}{\partial t} + (\rho c_{\mathrm{p}})_{\mathrm{l}}(V_{\mathrm{l}} \cdot \nabla) T = \phi \nabla(K_{\mathrm{l}} \nabla T) + \phi q_{\mathrm{l}} \tag{3}$$

Where $(\rho c_{\mathrm{p}})_{\mathrm{l}}$ is specific heat capacity of fluid (J/(kg•K)); K_{l} is thermal conductivity of fluid (W/(m•K)); q_{l} is heat source intensity of fluid.

Considering the compatibility of Eq. (2) and Eq. (3), the energy conservation equation for porous media is

$$(\rho c_{\mathrm{p}})_{\mathrm{t}} \frac{\partial T}{\partial t} + (1-\phi) T_0 \gamma \frac{\partial \varepsilon_{\mathrm{v}}}{\partial T} + (\rho c_{\mathrm{p}})_{\mathrm{l}}(V_{\mathrm{l}} \cdot \nabla) T = \nabla \cdot (K_{\mathrm{t}} \cdot \nabla T) + q_{\mathrm{t}} \tag{4}$$

$$(\rho c_{\mathrm{p}})_{\mathrm{t}} = \phi(\rho c_{\mathrm{p}})_{\mathrm{l}} + (1-\phi)(\rho c_{\mathrm{p}})_{\mathrm{s}} \tag{5}$$

$$q_{\mathrm{t}} = \phi q_{\mathrm{l}} + (1-\phi) q_{\mathrm{s}} \tag{6}$$

$$K_{\mathrm{t}} = \phi K_{\mathrm{l}} + (1-\phi) K_{\mathrm{s}} \tag{7}$$

$$\gamma = (2\mu + 3\lambda)\beta \tag{8}$$

Where μ and λ are Lame Constant; β is linear thermal expansion coefficient (1/K); T_0 is absolute temperature under the application of stressless (K); q_{t} is heat source or sink for porous media; $(\rho c_{\mathrm{p}})_{\mathrm{t}}$ is specific heat capacity of porous media (J/(kg•K)); K_{t} is thermal conductivity of porous media (W/ (m•K)).

Mechanical equation

The mechanical equation is

$$-\nabla \cdot \boldsymbol{\sigma} = \rho \boldsymbol{g} \tag{9}$$

Where $\boldsymbol{\sigma}$ is total stress (Pa).

The compatibility of Eq. (1), Eq. (4), and Eq. (9) are the governing equations for THM coupling model.

The software

A model for establishing thermal-hydraulic-mechanical coupling models for fractured rocks is developed based on java language and Application builder of COMSOL, which can simplify the model building process, preserve the powerful multi-physical fields coupling function, and add the function of using ground temperature to predict water inrush. The running window of the software is shown in Figure 1. The available windows and user interface components consist of Menu toolbar, Quick access toolbar, Geometry toolbar, Multiphysics toolbar, Calculation toolbar, and Results toolbar. It is very convenient and simple for users to build a numerical model, instead of spending more time on studying the operation method of COMSOL. The numerical model settings can be easily set up, such as the geometric model and material parameters.

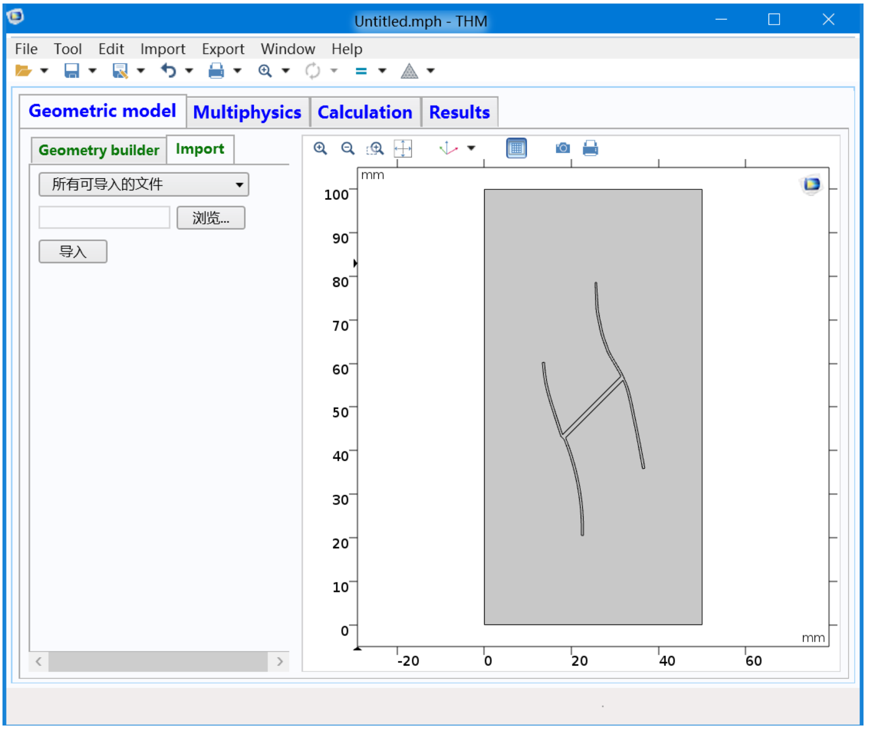


Figure 1 The running window of the software

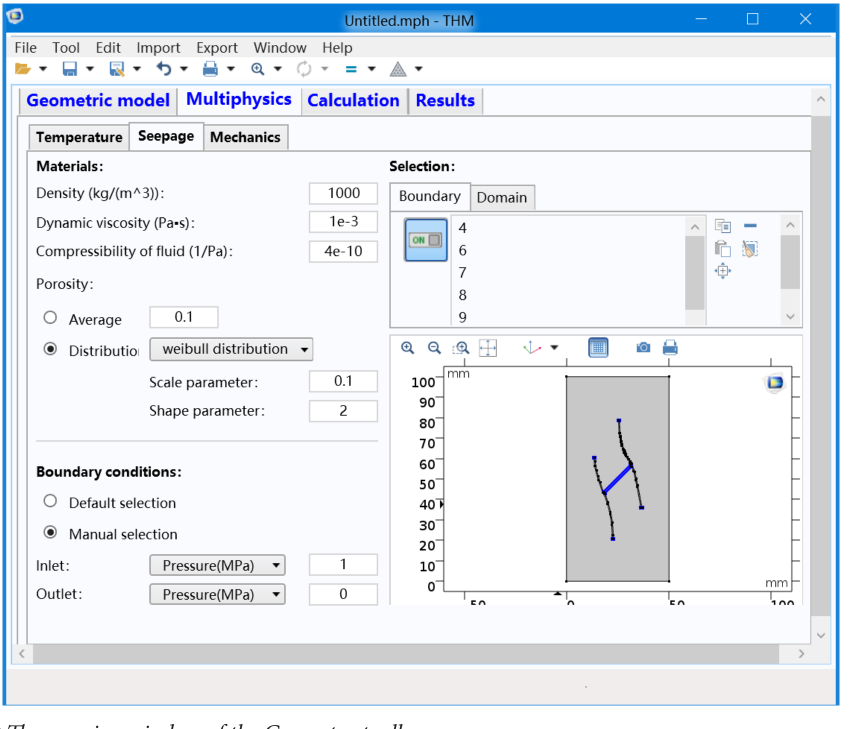


Figure 2 The running window of the Geometry toolbar

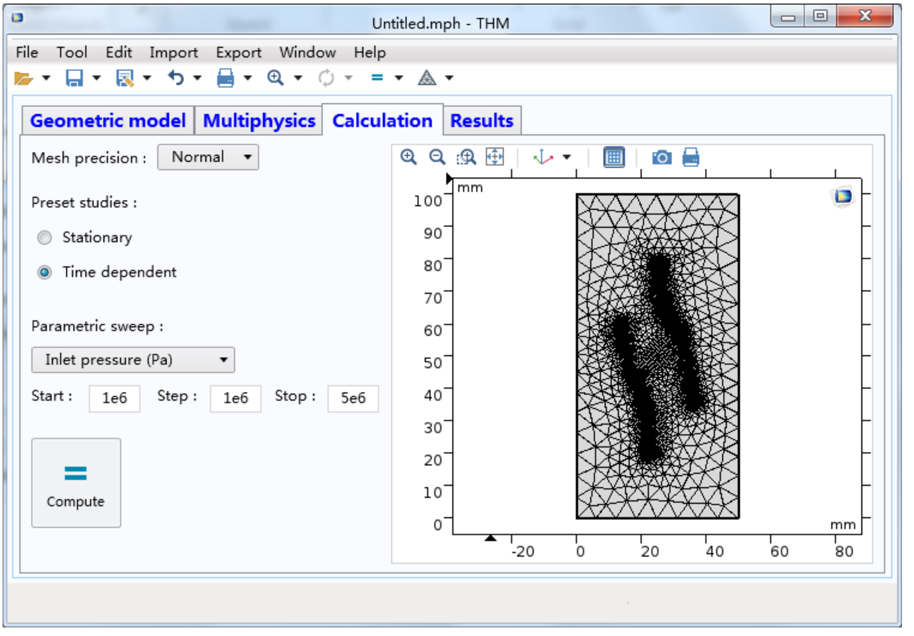


Figure 3 *The running window of the Calculation toolbar*

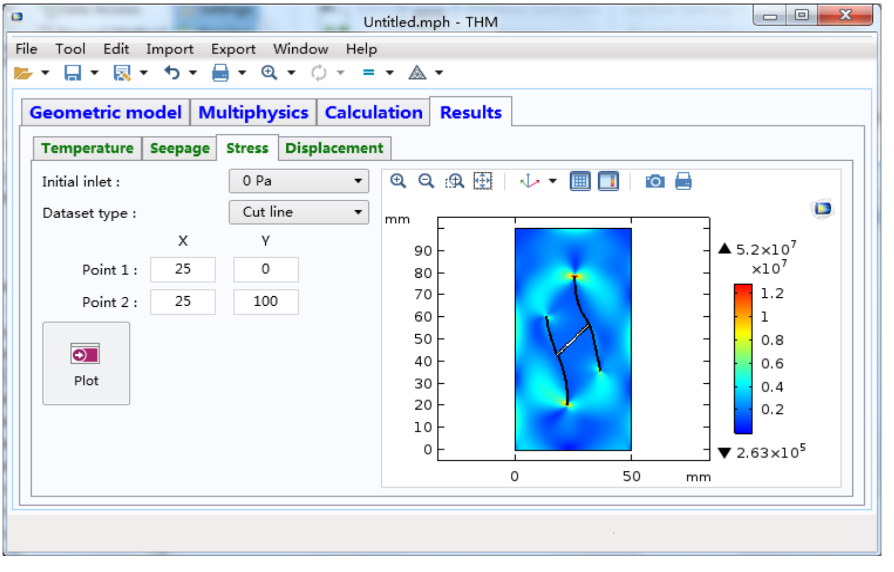
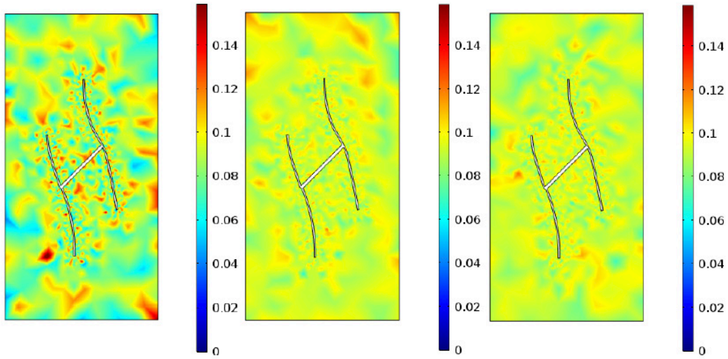


Figure 4 *The running window of the Results toolbar*

The running window of the Geometry toolbar is shown in Figure 1. The Geometry toolbar can provide two building geometry methods consisting of Geometry builder and import. The Geometry builder consists basic parameter settings and advanced settings. The advanced settings connect the MATLAB functions, which can provide pore settings.

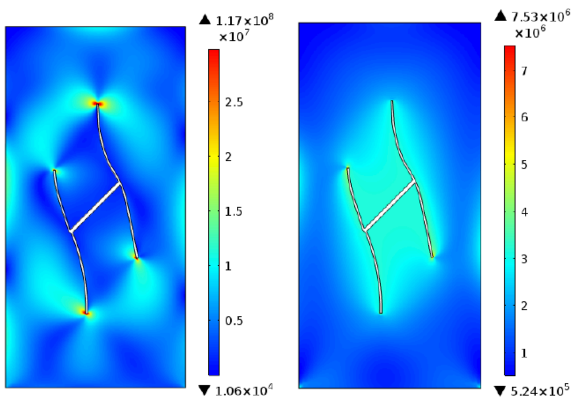
The running window of the Multiphysics toolbar is shown in Figure 2. The Multiphysics toolbar can provide the settings of thermal-hydraulic-mechanical coupling parameters.

The Calculation toolbar is shown in Figure 3. The Calculation toolbar can provide the boundary condition setting, mesh building function, mesh precision selection



a k =2 **b** k =6 **c** k =10

Figure 5 *The 2D and 3D geometric graphs at different shape parameters*



a *The fluid stres* **b** *The thermal stres*

Figure 6 *The distribution of the fluid stress and thermal stress*

function, study setting function (including stationary study, time dependent study and parametric sweep function), and calculation starting button.

The Results toolbar can output ground temperature calculation results. The running window of the Results toolbar is shown in Figure 4. The results can be saved and displayed in the form of picture, text, and video. The results of stress, seepage velocity, pressure, and et al. can be also output in the Results toolbar. In addition, the Results toolbar can provide the settings of the data set, such as the cut line and cut point.

THM coupling model

In order to study the effect of thermal-hydraulic-mechanical coupling environments on the fracturing characteristics of fractured rock, based on the previous triaxial experimental results of the author (Liu and Shen 2016), the fracture of specimen is processed to document format supported by the software. Then the document is imported into the software to build the geometric model. The porosity distribution has great influence on rock permeability. Therefore, the seepage toolbar can provide the advanced setting for the porosity distribution. The porosity distribution can be defined as random distribution or Weibull distribution. When the distribution type is Weibull distribution. As shown in Figure 5, the scale parameter λ is 0.1, which reflects the average porosity. The shape parameter k reflects the discrete degree of the porosity. The discrete degree decreases with decreasing shape parameter.

Figure 6 shows the fluid stress and thermal stress. The fluid stress concentration occurred in the wring crack tip, which contributes to

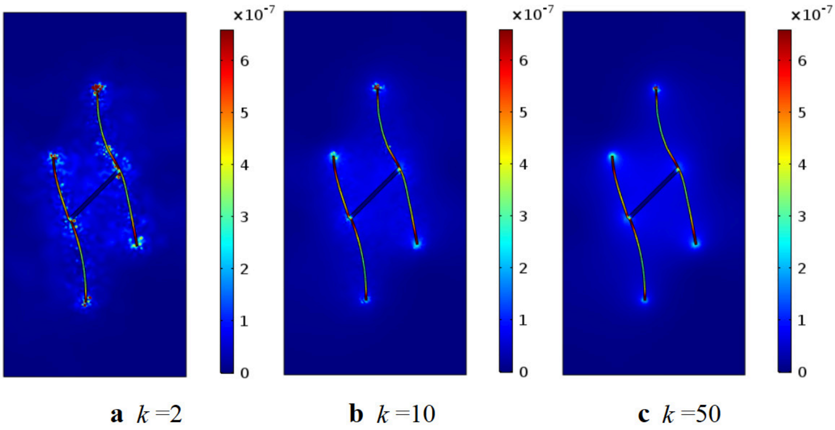


Figure 7 The distribution of the fluid velocity at different shape parameters

the crack propagation. The thermal stress mainly distributed in an area formed by connecting the wring crack tips.

Figure 7 shows the fluid velocity distribution at different shape parameters. When the shape parameter is 50, the rock porosity can be considered homogeneous. In this figure, the fluid flows out of the wring crack into the complete area. The area expands with decreasing shape parameters, especially around the wring crack tip, which indicates that the permeability increases with increasing rock heterogeneity and the increase of rock heterogeneity contributes the crack growth.

Conclusions

The software can provide a more convenient and efficient method to establish thermal-hydraulic-mechanical coupling models for fractured rocks. The discrete degree of real pore distribution can be well simulated by the random distribution or Weibull distribution. The discrete degree decreases with decreasing shape parameter. According to the THM coupling, the fluid stress concentration occurred in the wring crack tip, which contributes to the crack propagation. The thermal stress mainly distributed in an area formed by connecting the wring crack tips. The permeability increases with increasing rock heterogeneity and the increase of rock heterogeneity contributes the crack growth.

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