A combined aperture model of an enhanced geothermal system using coupled thermo-hydro-mechanical simulation

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Abstract

To date, most existing fracture aperture models are limited to compression-induced closure and shear-induced dilation for the analysis of heat extraction in enhanced geothermal system (EGS) reservoirs. This paper presents a new, fully coupled thermo-hydro-mechanical (THM) model to investigate the combined effect of shear, thermal and compression stresses on fracture aperture alterations during the heat extraction process. A brief analysis determines the underlying mechanisms characterising these coupled THM processes. The results provide insights into the fracture aperture's transient behaviour during exploitation, which is a crucial factor in optimising thermal energy production in EGS reservoirs.

Key words: *Shear-induced dilation; Thermal-induced opening; Compression-induced closure*

1. Introduction

Stimulating the crystalline formation to open predominantly pre-existing natural fractures, in order to create a reservoir, is the first step towards extracting heat from an enhanced geothermal system (EGS) [1]. The second step involves circulating fluid through the fractures to create a connection between wellbores [2]. During circulation, the fracture aperture dilates, opens and closes due to heat extraction. The complex interaction resulting in fracture aperture changes during exploitation includes shear-induced dilation, thermal-induced opening and compression-induced closure. Bandis et al. [3] and Barton et al. [4] conducted several experiments on different rock samples that enabled them to develop several mathematical expressions of rock joints' behaviour, which have become widely accepted in rock mechanics. Hick et al. [5] and Willis-Richards et al. [6] developed specific mathematical models of fracture aperture response during heat extraction in hot dry rock (HDR) geothermal reservoirs.

The above-cited works focus solely on shear-induced dilation and compression-induced closure in fracture apertures. However, several other authors [7] have also pointed out that the effect of the thermal-induced opening could influence fracture apertures' behaviour. It is therefore crucial to investigate the effects both of individual models and of combinations of different models on aperture opening/closure during EGS exploitation. On this background, this study presents models of shear-induced dilation, thermal-induced opening and compression-induced closure. The models are implemented in the COMSOL Multiphysics solver using a coupled thermo-hydro-mechanical (THM) approach, in order to examine how they respond to heat extraction in EGS reservoirs.

2. Mathematical description

The mathematical formulation of the fracture aperture model is derived from laboratory observation of several rock joint samples [3], [4]. When fluid flows in the fracture, the surfaces are held apart by internal fluid pressure p. The effective stress at the surface of the fracture is given as

$$\sigma_n' = \sigma_n - p \quad (1)$$

where σ_n is the normal stress to the fracture surface and p is the fluid pressure in the fracture. The closed fracture aperture ($\sigma'_n > 0$) can be expressed as [4]

$$b = b_0 - \frac{\sigma'_n}{K_n + \frac{\sigma'_n}{b_{\max}}} + b_s + b_{res} \quad (2)$$

where b_0 is the aperture at zero normal stress, K_n is the normal stiffness of the fracture, $b_{\max}$ is the maximum fracture closure, b_s is the change in the aperture resulting from any subsequent shear accumulated, and b_{res} is the residual aperture at high effective stress [6]. Stress field perturbation due to fracture fluid pressurisation could result in shear slip and instability at the fracture surfaces. A simple friction law defines shear stability. Shear slip occurs when the shear force exceeds the confining frictional force, written as [6]

$$\tau > \sigma'_n \tan\left(\phi_{basic} + \phi_{dil}^{eff}\right) \quad (3)$$

where ϕ_{basic} is the basic friction angle, a material property of the fracture surfaces, ranging between 30° and 40°. The effective shear dilation angle ϕ_{dil}^{eff} is a property of both fracture surfaces and normal stress. The available fracture shear stiffness and excess shear stress determine the amount of shear displacement, expressed as [8]

$$U_s = \frac{\Delta\tau}{K_s} \quad (4)$$

where K_s is the fracture shear stiffness and $\Delta\tau$ is the excess shear stress, written as [8]

$$\Delta\tau = \tau - \sigma'_n \tan\left(\phi_{basic} + \phi_{dil}^{eff}\right) \quad (5)$$

Thus, the increment in aperture due to shear dilation, b_s, can be written as [6]

$$b_s = U_s \tan\left(\phi_{dil}^{eff}\right) \quad (6)$$

Substituting (7) into (2) and letting $b_{res} = 0$, the total aperture can be expressed as

$$b = b_0 - \frac{\sigma'_n}{K_n + \frac{\sigma'_n}{b_{\max}}} + U_s \tan\left(\phi_{dil}^{eff}\right) \quad (7)$$

Thermoelasticity also contributes to the changes in the fracture aperture. Assuming complete spherical symmetry in the temperature distribution, the thermal stress can be calculated as

$$\sigma_T = \frac{2\alpha E}{3(1-\nu)}\left(T_0 - T\right) \quad (8)$$

where α is the thermal expansion coefficient of the rock, E is the Young's modulus of the rock, ν is the Poisson's ratio, T_0 is the initial rock temperature, and T is the rock temperature at any given time t. Substituting (10) into (1) yields

$$\sigma'_n = \sigma_n - \left(p + \sigma_T\right) \quad (9)$$

Expression (9) is the effective stress across the fracture relating to normal stress, pore pressure and thermal stress. Fig. 1 presents the reservoir geometry employed in this study. The reservoir geometry, initial and boundary conditions, and material properties are similar to those employed in Ref [9]. The only difference is the wellbore spacing, which is 400 m here. These data, together with equations (1–9), as introduced in this section, and the governing equations and the THM coupled processes framework presented in Ref [10], are implemented in the COMSOL Multiphysics solver. The simulation results are presented in the following section.

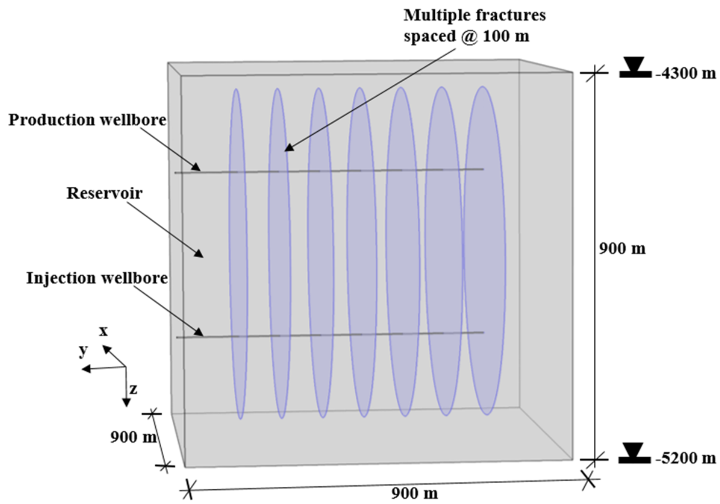

Fig. 1. Reservoir geometry

3. Simulation results

Fig. 2 presents the fracture aperture opening and the corresponding permeability changes for the different models during a long-term simulation of 30 years. The results show that shear dilation affects the aperture the most, followed by thermal stress. Compression-induced closure/opening has the least impact during the heat extraction process.

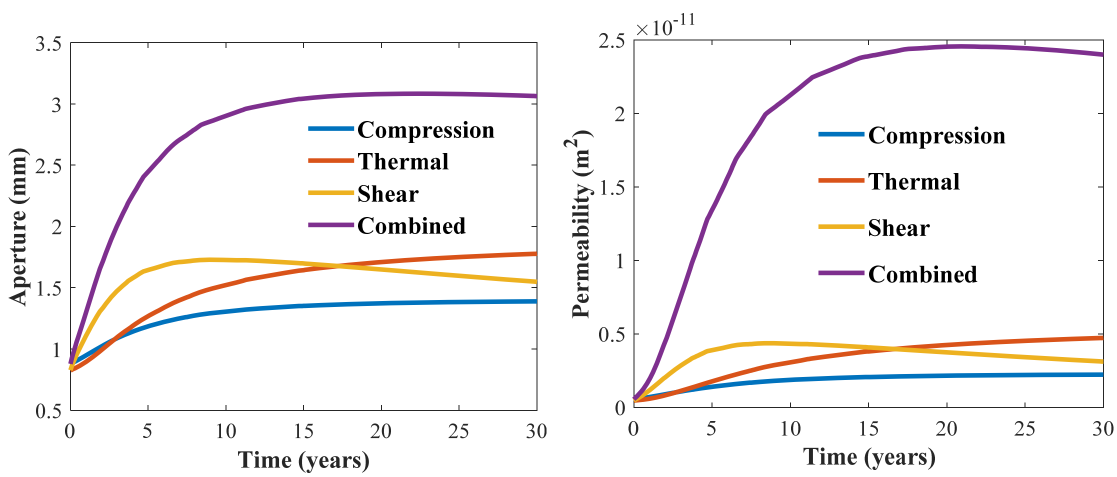

Fig. 2. Fracture aperture opening (Left) and permeability changes (Right) for the compression, thermal, shear, and combined models

Fig. 3 displays the aperture propagation on the middle fracture surface at various simulation stages for the different aperture models. The results show that in earlier stages, the aperture evolution is only pronounced at the injection location. In the later stages, however, the aperture evolves upwards towards the producer in the thermal, compression and combined models. For the shear case, the aperture opening extends laterally due to shear dilation effects.

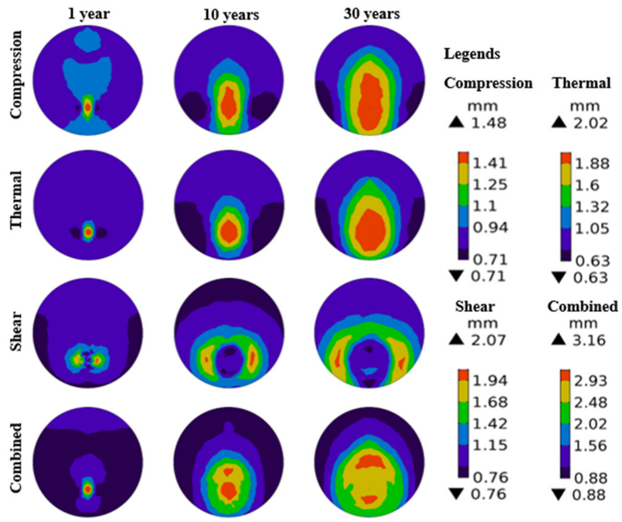

Fig. 3. Fracture aperture propagation for all the models at different simulation times

4. Conclusions

This work has presented a new fracture aperture modelling framework incorporating thermal-induced opening, shear-induced dilation and compression-induced closure. Each model is developed using a coupled THM approach in the COMSOL Multiphysics finite element-based solver. The results show that each of the models contributes to permeability enhancement; however, the combined effect of all the models together yields the greatest reservoir productivity.

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