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A semi-analytical correlation of thermal-hydraulic-mechanical behavior of fractures and its application to modeling reservoir scale cold water injection problems in enhanced geothermal reservoirs

Shihao Wang[a], Zhaoqin Huang[a,b,*], Yu-Shu Wu[a], Philip H. Winterfeld[a], Luis E. Zerpa[a]

[a] Department of Petroleum Engineering, Colorado School of Mines, Golden, CO, USA
[b] School of Petroleum Engineering, China University of Petroleum, East China, Qingdao, People's Republic of China

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ABSTRACT

Fractured enhanced geothermal system (EGS) reservoirs are typically sensitive to thermal and mechanical change induced by cold water injection. It has been observed that the permeability at the cold water injector is significantly enhanced. The physical thermal-hydrologic-mechanic (THM) process behind this phenomenon is that, the injection of cold water decreases the temperature of the reservoir rock and causes the matrix block to shrink, resulting in an increase of the fracture aperture and fracture permeability. Therefore, it is of great importance to quantify the effect of thermally induced fracture aperture change to better predict the behavior/performance of EGS reservoirs.

In this work, we develop a novel correlation of the thermal-induced normal change of fracture aperture. The new correlation is based on the analytical solution of the governing displacement equations. Compared to the existing empirical correlations, the new correlation can better describe the physical processes by including the thermal effect on the matrix-fracture deformation. We have verified this correlation with respect to refined simulation results and implemented this correlation in a fully coupled massively parallel geothermal simulator, THM-EGS. We have applied this correlation to study field scale problems with certain parameters from Habanero Field in Copper Basin, Australia. Our results demonstrate that the fracture permeability near the cold water injector could be enhanced 7 times.

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1. Introduction

It is widely accepted that fractures are important to geothermal reservoirs. Many types of fractures are sensitive to pressure and stresses, especially the natural fractures that are penetrated by wells or re-activated by hydraulic fractures. Meanwhile, cold water injection can cause the matrix to shrink and the aperture of the surrounding fractures will be thus increased (the thermal unloading process), resulting in an enhancement of permeability at the area that is close to the injector. Such combined thermal-hydro-mechanical effects of injection and production can dramatically change the properties of fractures (Gelet et al., 2012), or even close some of them, resulting in a huge variation in the conductivity (Settari and Mourits, 1998; Settari and Walters, 2001; Jaeger et al., 2009; Wu et al., 2011)

Fractured reservoirs can be modeled by either discrete fracture method (Barenblatt et al., 1960; Warren and Root, 1963). In discrete fracture method, the geometry of the fracture network is explicitly modeled, while in the dual continuum approach, the fracture network and the matrix rock are modeled as two continuum with average pressure and temperature. Discrete fracture method is naturally more accurate by capturing more flux behaviors between the fracture and the matrix rock (Moinfar et al., 2011). However, the characterization of the fracture network highly depends on the accuracy of logging and geostatistical techniques. Dual continuum method, on the other hand, is more convenient to implement. Moreover, multiple porosity methods, such as MINC (Karsten Pruess, 1985), more accurately describe the flow behavior inside the matrix, by further dividing the matrix rock into multiple continuums.

Injectivity increase phenomena near the cold water injector have been widely observed in geothermal reservoirs (Stefansson and V.-đur, 1997; Kaya et al., 2011). In Geyser geothermal field, micro-earthquake events near the cold water injector have also been recorded and studied (Majer and Peterson, 2007; Rutqvist,

* Corresponding author at: Department of Petroleum Engineering, Colorado School of Mines, Golden, CO, USA.
E-mail addresses: huangzhqin@gmail.com, huangzhqin@upc.edu.cn (Z. Huang).

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Nomenclature

A	Interface area of a connection (m^2)
a	Exponential parameter for porosity (dimensionless)
b_i	fracture aperture on the ith direction (m)
d_β^k	diffusive coefficient of component k in phase β (m^2/s)
E	Young's modulus (Pa)
F	flux term (m/s)
G	shear modulus (Pa)
g	gravity terms (m/s^2)
h	specific enthalpy (J/kg)
k	component index (dimensionless)Component index (dimensionless)
K_0	Absolute permeability (m^2)
K_r	Relative permeability (dimensionless)
K_R	Formation heat conductivity (W/m K)
K_β	Liquid heat conductivity (W/m K)
L_i	Fracture spacing along the ith direction (m)
M	Accumulation term (kg/m^3 s)
Q	Generation term (kg/m^3 s)
p	Pore pressure (Pa)
Pc	Capillary pressure (Pa)
S	Phase saturation (dimensionless)
T	Temperature (K)
T_f	Fracture temperature (K)
T_m	Matrix temperature (K)
T_{ref}	Reference temperature (K)
Δt	Length of time step (s)
$\bar{u}$	Displacement vector (m)
u_β	Internal energy of phase β (J/kg)
V	Volume (m^3)
x	Mass component (dimensionless)
α	Biot's coefficient (dimensionless)
β	Phase index (dimensionless)
β_T	Linear thermal expansion coefficient (m/m·K)
ε_k	Diagonal strain component (dimensionless)
ε_v	Volumetric strain (dimensionless)
ε_{kk}	Diagonal strain component (dimensionless)
λ	Lame's coefficient (dimensionless)
μ	Viscosity (Pa·s)
$\nu_{max,hor}$	Maximum horizontal stress (Pa)
$\nu_{min,hor}$	Minimum horizontal stress (Pa)
ρ	Density (kg/m^3)
σ'	Effective stress (Pa)
σ_k	Normal stress along the kth direction (Pa)
σ_{kk}	Diagonal stress component (Pa)
σ_m	Mean stress (Pa)
$\sigma_n^{'}$	Normal effective stress (Pa)
ϕ	Porosity (dimensionless)
τ_0	Intrinsic tortuosity of the rock (dimensionless)
τ_β	Tortuosity correction of phase β (dimensionless)

2008). Such observations could be explained by the shrinkage of rock induced by change of thermal stress field. Specially, in fractured geothermal reservoir, the injected cold water causes the matrix rock to shrink, increasing the fracture aperture. As the fracture permeability is approximately the cubic power of the fracture aperture, the increase of fracture permeability could be considerable.

In this work, we aim to develop a practical fracture aperture correlation to be used in the fully coupled THM simulation of fractured geothermal reservoirs, in order to quantify the thermal stress effect. Our correlation is based on the Navier's displacement equation, combined with the dual-porosity model. Our correlation can be used in the accurate calculation of cold water injectivity as well as the cold front breakthrough time. The correlation is easy to implement in reservoir simulators. It can also be used in existing simulators even without a mechanical simulation module. The details of the derivation of the correlation and its application are described in the following sessions.

2. Literature review

2.1. Dual porosity model

In reservoir simulation, dual porosity model has been widely used to characterize interconnected fracture system. In the dual porosity model, the fractured system is divided into two types of grid blocks, which are the fracture and the matrix. While the fracture system serves as the major flow channel, the matrix blocks play the role as the fluid storage system. The transmissibility between the fracture system and the matrix block is represented by the concept of a 'shape factor'. The flow rate between the matrix and the fracture is calculated using the following equation.

$$q = \sigma \frac{k_m}{\mu} V_m \left(\bar{P}_m - P_f\right) \tag{1.1}$$

In the above equation, V_m is the volume of the matrix block and σ is the shape factor. The shape factor can be determined by analytical or semi-analytical (Barenblatt et al., 1960; Warren and Root, 1963; Kazemi et al., 1976; Gilman and Kazemi, 1983; Chang, 1993; Zimmerman et al., 1993; Lim and Aziz, 1995).

Recent advances in dual porosity model include the extension to thermal flow (van Heel et al., 2008) and multiphase flow (Lu et al., 2008). In this work, we use the dual porosity model to simulate the fluid flow inside the EGS reservoir.

2.2. Fracture aperture correlation

The normal closure of a set of fractures is just the normal displacement of the fracture, and it is directly related to the effective normal stress that is on the fracture planes. There are mainly two types of models, known as the hyperbolic model and the logarithmic model, to correlate the fracture aperture with the effective normal stress. Among the correlations belonging to the hyperbolic model, the Barton-Bandis' correlation (Bandis et al., 1983; Barton et al., 1985; Bandis, 1990)is the most widely used, and it is shown in the following equation,

$$\Delta b = \frac{\Delta \sigma'_n}{k_n - \frac{\Delta \sigma'_n}{\Delta b_{\max}}} \tag{1.2}$$

where $\sigma_\mathrm{n}^{'}$ is the effective normal stress. Δb is the aperture change (closure), while Δb_{max} is the maximum closure. k_n is the stiffness along the normal direction. Evans' model (Evans et al., 1999) is a widely used logarithmic model, as shown in the following equation,

$$\Delta b = -\left(\frac{dk_n}{d\sigma'_n}\right)^{-1} \ln\left(\frac{\sigma'_n}{\sigma'_{ni}}\right) \tag{1.3}$$

where the $\sigma_\mathrm{ni}^{'}$ is the reference effective normal stress.

Rutqvist and Tsang (2003) substituted the hyperbolic model into the cubic law of fracture permeability to calculate the transmissibility of the fractures, as shown in the following equation.

$$T = C\left[b_{ni} + \frac{\sigma'_{ni}}{k_{ni}}\left(1 - \frac{\sigma'_{ni}}{\sigma'_n}\right)\right]^3 \tag{1.4}$$

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