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THM (Thermo-hydro-mechanical) coupled mathematical model of fractured media and numerical simulation of a 3D enhanced geothermal system at 573 K and buried depth 6000–7000 M

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ABSTRACT

Hot dry rock geothermal energy is almost inexhaustible green energy. However, it makes slow progress in practice due to slow theory development. In this study, a three dimension thermo-hydro-mechanical coupled model of fractured media was established to simulate the extraction of HDR (Hot dry rock) geothermal energy based on the geological characteristics (geothermal gradient of 50 K/km, buried depth of 6250–6750 m) of Tengchong geothermal field in China. The simulation results show the variation in both field of temperature, stress, seepage and fracture aperture during heat extraction. The temperature in fracture face increased exponentially from injection well towards production well while extracting heat. The initial rock mass temperature of 573 K decreases to 423 K after 9-year running. The initial water pressure gradient in the fracture reached 0.17 MPa/m near the injection well and then decreased to 0.052 MPa/m after 1 year. The fracture aperture was triple of the initial value and the permeability coefficient increased by nine times over the 9-year operation period. That seepage resistance of artificial storage reservoir gradually decreased could improve extracting geothermal energy more efficiently. The amount of extracted heat declined exponentially with running time. The total extracted geothermal energy over 9 years was 5977 MWa and rock mass temperature decreased to 423 K.

1. Introduction

HDR (Hot dry rock) geothermal energy is an inexhaustible energy resource. Large-scale investigations [1–3,7,9,12–14], were conducted around the world following the successful testing of the United States Fenton Hill geothermal site in 1984. In these studies a new type of enhanced geothermal system was proposed in which an artificial storage layer is created by multiple vertical cracks produced by horizontal drilling. The studies investigated the heat exchange, heat transfer, fluid migration, rock mass deformation, and the coupling effect surrounding an EGS (enhanced geothermal system) underground artificial heat exchange system. Kohl et al. [4] modeled coupled THM (thermo-hydro-mechanical) processes in a single fracture using linear thermo-poroelastic effects. Taron and Elsworth [15] studied THMC (thermo-hydro-mechano-chemo) coupling effects in dual porosity media where porosity and permeability change as a result of changes in stress and chemical precipitation and dissolution. Pandey et al. [10] investigated the evolution of the fracture aperture under the effects of THC (thermo-hydro-chemical) coupling. Ghassemi and Zhou [11] coupled fracture flow and heat transport to thermo-poroelastic deformation in a discretely fractured reservoir and examined the changes in temperature, pressure, and aperture with time. Fox et al. [8] studied multi-fracture systems, and derived the temperature mass flow law for geothermal energy extracted at fracture spacing of 200 m, 100 m, and 50 m. Zeng et al. [5,6] investigated HDR in the Desert Peak geothermal field in American through a single vertical fracture and horizontal fracture. The underground heat exchange system included complex convection heat transfer and heat exchange in fractured media, water migration, and rock mass deformation. They also considered chemical dissolution and diffusion caused by changes in the HDR with depth and scale.

It is more special for numerical simulation of hot dry rock geothermal energy extraction to consider coupling effect of hot fluid transmission-fractured rock mass deformation-heat transfer in artificial hydrofracturing. In particular less studies is conducted on the variations of stress field, fracture opening, permeability during extracting geothermal energy from hot dry rock. However,

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Nomenclature

λ	one of the lame constant [M L^{-1} T^{-2}]
μ	one of the lame constant [M L^{-1} T^{-2}]
U_i	solid displacement component [L]
F_i	applied to rock mass body force component [M L^{-2} T^{-2}]
β_s	$\beta_s = \alpha E/(1-2\nu)$ [M L^{-1} T^{-2}]
α	linear thermal expansion coefficient of rock [K^{-1}]
E	elastic modulus [M L^{-1} T^{-2}]
ν	poisson's ratio
T	temperature [K]
t	time [T]
T_r	temperature of rock matrix [K]
K_n	crack normal stiffness [M L^{-1} T^{-2}]
K_s	crack tangential stiffness [M L^{-1} T^{-2}]
σ'_n	effective normal stress component to fracture [M L^{-1} T^{-2}]
σ'_s	effective tangential stress component to fracture [M L^{-1} T^{-2}]
ε_n	normal strain component to crack
ε_s	tangential strain component to crack
σ_n	total normal stress component to crack [M L^{-1} T^{-2}]
P	water pressure in pore or crack [M L^{-1} T^{-2}]
β_A	ratio of the connected area to total area of crack
K	Kelvin temperature unit
cpr	specific heat of the rock matrix [L^2 T^{-2} K^{-1}]
cpw	specific heat of the water [L^2 T^{-2} K^{-1}]
ρ_r	density of rock matrix [M L^{-3}]
λ_r	thermal conductivity of rock-matrix [M L T^{-3} K^{-1}]
W	source sink term of heat [M L^{-1} T^{-3}]
ρ_w	density of water [M L^{-3}]
T_w	water temperature [K]
λ_w	thermal conductivity of water [M L T^{-3} K^{-1}]
kfi	water permeability coefficient in I crack [L T^{-1}]
Trb	fracture surface temperature [K]
b	crack aperture [L]
q_i	water specific flux [L T^{-1}]
Φ	crack porosity
β_2	water compressibility
e	rock matrix volume deformation
s	crack tangential coordinates [L]
σ'_{ij}	effective stress tensor [F L^{-2}]
ε_{ij}	strain tensor
ε_{kk}	volume strain
δ_{ij}	kronecker symbol
δ_w	function of p and T, not exceed 6% of $1/\rho_w$

these changes will have significant influence on economic profits and sustainability of extracting hot dry rock geothermal energy. Further theoretical research and numerical simulation of HDR geothermal energy extraction is still needed. Very few investigations of topics such as EGS construction at high temperature and depth, analyses of rock mass deformation and fracture, and heat transfer and pressure variation have been carried out under the relatively strict THM coupling effect.

In the paper, a theoretical model of fractured rock mass deformation, seepage, and heat transfer was established with a combination of fine and coarse grids and numerically simulated fracture faces of injection and production wells in the HDR EGS. The modeling included variations in temperature, stress, and fluid pressure of rock mass at depth of 6000–7000 m and temperature of 573 K. This model investigated the evolution of aperture, water pressure, and temperature in fracture, and the evolution of the heat extraction capacity in the constant pressure mining system with time. In addition, the heat recovery of the geothermal extraction system after the mining ended was analyzed.

2. Mathematical model of fractured media THM coupling

2.1. Physical considerations

In the geothermal extraction system, the rock mass as a direct carrier of fluid migration and heat transfer can be simplified as a fracture media model consisting of a matrix rock block and a fracture. When establishing the mathematical model of the fractured media THM coupling, we assumed the following:

(1) The rock mass structure is composed of fractures and a matrix rock block of dual media containing pores and cracks.
(2) The matrix rock block of the rock mass can be simplified as continuous media with homogeneous isotropic elastomers; the rock mass fracture can be simplified as fracture media.
(3) Compared with the fissures, the water storage capacity and water permeability of the matrix rock block are very weak; thus, they can be neglected in the mathematical model.
(4) The fracture seepage law complies with Darcy's Law:

$$q_i = -k_{fi}\frac{\partial p}{\partial s_i} \quad i = (1,2) \tag{1}$$

where $k_{fi} = (b^2/12)$ is the fracture permeability coefficient and b is the fracture aperture, p is pressure of fracture, s_i is a coordinates along with surface fracture.

(5) The fracture deformation agrees with the joint unit model.
(6) The water does not vaporize because it is under high pressure; we assume that the rock mass is saturated with single-phase water.
(7) The effective stress law of rock mass fracture is $\sigma' = \sigma - \beta_A p$, where β_A is the ratio of the connectivity area to the total area in the rock mass fracture.
(8) The matrix rock blocks comply with the thermo-elastic constitutive law as follows:

$$\sigma'_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + \frac{E}{1+\nu}\varepsilon_{ij} - \frac{E}{1-2\nu}\alpha\Delta T\delta_{ij} \tag{2}$$

where α is the thermal expansion coefficient of the rock mass [1/K], ΔT is the temperature increment of the rock mass, E is the elastic modulus, ν is Poisson's ratio, λ is the Lamé constant, and δ_{ij} is the Kronecker symbol.

(9) The density of the water is no longer a constant but a function of pressure and temperature, $\rho_w = \rho_w(p, T_w)$ and is expressed as follows:

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