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Determination of optimum parameters of doublet system in a horizontally fractured geothermal reservoir

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ABSTRACT

The parameters for the optimum production temperature of a geothermal well were determined by using both an analytical and convective conductive heat transfer numerical model. The numerical model was verified with the available analytical solutions. The production temperatures for different mass flow rate, number of fractures, fracture width, and production time were combined to obtain the minimum fracture length and the half spacing. The velocity profile in a single fracture was incorporated in the numerical model in deriving the minimum fracture length that allows for target production temperature. A nomogram solution is also presented for the evaluation of the production temperature that incorporates the mass flow rate, fracture width, fracture length, number of conductive fractures, host rock temperature, and the production time. The minimum fracture half spacing was investigated in order to prevent thermal interference between the fluid-carrying fractures by using the numerical model. The minimum fracture length is determined to be 600 m for maintaining 10% thermal drawdown after 10 years of production with 20 fractures when the mass flow rate and fracture width are 40 kg/sec and 100 m, respectively. The results from this study can provide a preliminary guideline to optimize the various design parameters involved in hydraulic stimulation and geothermal production in the EGS reservoir.

1. Introduction

Geothermal energy provides an option for renewable energy for base load electricity in alleviating the world's energy and climate predicament [1]. In order for geothermal power generation to become a major energy source, development in non-volcanic areas is essential [2]. The most common form of geothermal energy extraction involves injecting cold water through an injection well and extracting heated water from a production well [3]. However, the main challenge for fluid circulation at depth is the low permeability of the host rock. Therefore, the hydraulic stimulation is carried out to enhance the permeability of the host rock. The Enhanced Geothermal Systems (EGS), technology that can be applied in non-volcanic areas, circulates the water between the injection and the production wells, extracting the stored geothermal energy in the reservoir at depths of 3–7 km [1]. A key consideration is to obtain various design parameters such as thermal performance, hydraulic performance, flow rates and water recovery, injection pressure, and fracture statistics that optimize the production temperature in a sustainable manner [4].

Extensive research has been carried out on the parameters and processes affecting the geothermal extraction. Such research includes thermal, mechanical, and hydraulic (T–M–H) coupled numerical models as well as analytical studies. The long-term performances of geothermal reservoirs were studied by Kohl et al. [5,6] using the numerical model for coupled hydraulic, thermal and mechanical responses including the closure of fractures. The numerical model developed by Ghassemi and Zhou [7] considered the variation of fracture aperture to pressure changes as well as the impact of the coupled poro-thermoelastic processes when cold water was injected into an arbitrarily shaped fracture in geothermal reservoirs. Vogt et al.'s [8] approach tried to capture the additional flow pathways in the main fluid carrying fault, using a Monte Carlo model to reveal the pathways indicated by the tracer experiments. Rutqvist et al. [9] combined TOUGH2 and FLAC3D to study the multiphase fluid flow and coupled thermal–hydrological–mechanical (THM) processes in porous and fractured geological media. A numerical model that integrates fluid flow, permeability tensor, and heat transfer was described by Shaik [10]; the approach was applied to predict the production temperature of naturally fractured geothermal reservoirs.

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The analytical solutions presented by Gringarten et al. [11] were applied to parallel equidistant vertical fractures. In fact, their equivalent temperature approach can be incorporated to highlight the importance of the multi-fracture concept in the geothermal energy extraction. Meanwhile, the analytical model developed by Yang and Yeh [12] can be used to obtain geothermal production temperature. Their approach involved a numerical inversion of the Laplace transform to determine the fluid temperature. They further demonstrated the importance of well spacing, the radius of the well, reservoir thickness, and the flow rate in a multi-well system.

Coupled numerical processes applied to the modeling of geothermal energy can be classified into five systems considering the physical phenomena taking place in geothermal reservoirs as rock stresses responding to fluid pressure changes (H–M), rock stresses responding to temperature changes (T–M), fracture flow apertures responding to stress changes (M–H), heat advection by flowing water (H–T), and viscosity and flow patterns changing with temperature (T–H) [13]. As pointed out by Richards and Wallroth [14], any geothermal reservoir modeling should be able to evaluate one or more of the five physical phenomena in the geothermal reservoirs during the simulation process.

The economic feasibility of a geothermal reservoir depends on the history of production temperature, fluid loss during the circulation, and pumping energy requirements which is also closely related to the reservoir hydraulic performance. A detailed description of the importance of proper reservoir path design was presented elsewhere [4,15]. Another important parameter for sustainable geothermal extraction is the lifetime of the geothermal reservoir, which has two definitions: the time required to recover the entire investment and the year when the production temperature drops below the given threshold value for ensuring the efficiency of the power generation [16]. The thermal drawdown study carried out by Wunder and Murphy [17] showed that a reservoir thermal recovery process can be determined using a numerical method.

In the present study, fluid-carrying fractures are simulated as through-going fractures with non-isothermal fluid flow to study the characteristics and critical parameters associated with the long-term production of geothermal fluid. A nomogram solution is presented to determine the production temperature of the horizontally fractured geothermal wells combining the horizontal fracture length, fracture width, number of conductive fractures, mass flow rate and the production time. We discuss the minimum horizontal fracture length in relation to the maximum temperature gain and the minimum half spacing in order to avoid the thermal interference between two horizontal fluid-carrying fractures within the system lifetime. Some of our numerical results are compared with the available analytical solutions. The histories of the production temperatures with different shutdown periods were also analyzed. The second geothermal extraction periods after the different shut-down periods were numerically simulated.

2. Governing equations

The fluid flow in the fractures can be reasonably assumed to be driven by an externally imposed pressure gradient through two stationary flat walls. We consider the incompressible, laminar, and single-phase flow inside a horizontal fracture. The analysis of the heat extraction from the hot rock was carried out by making the following basic assumptions: (1) the rock matrix is homogeneous, isotropic, and impermeable which is a reasonable assumption for crystalline rock; (2) viscosity of water, densities and specific heats of both the water and rock and the thermal conductivity of the rock are constant; (3) the heat is transferred vertically by conduction in the rock and horizontally by convection within the fracture; (4) the temperature of both the water in the fracture and the rock is initially the same; and (5) there is no heat generation or dissipation in the rock domain; (6) the temperature of fluid is constant over the fracture aperture. Therefore, the governing equations should describe the heat transfer by conduction process in the rock domain and the heat transfer by forced convection [18] in the fluid domain. The relevant equations involving the temperature can be expressed as given in Eq. (1) and Eq. (2) [19–22].

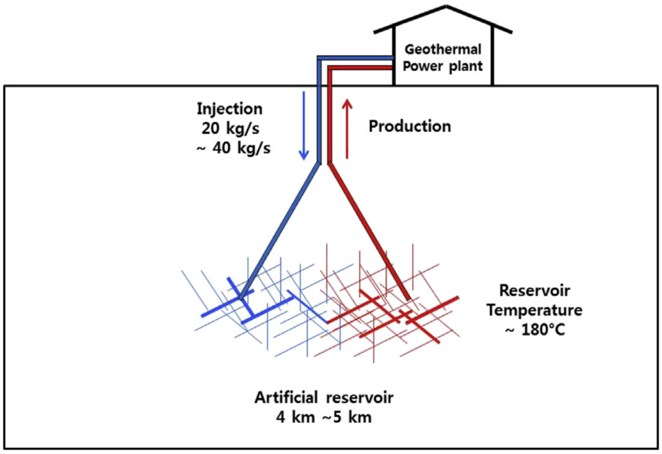

Fig. 1. Conceptual diagram showing the EGS geothermal production in Pohang, Korea.

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

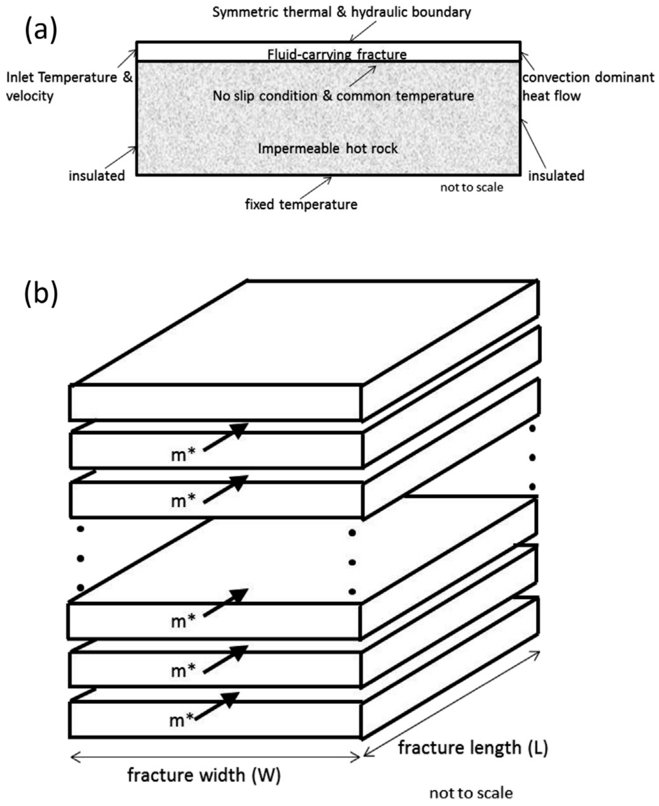

Fig. 2. Geometry used for this study. (a) Configuration of the numerical model and its boundary conditions, (b) fractured reservoir with multiple fractures.