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Design, modeling, and evaluation of a doublet heat extraction model in enhanced geothermal systems

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ABSTRACT

A conceptual Enhanced Geothermal System (EGS) model, where water is circulated through a pair of parallel injection and production wells connected by a set of single large wing fractures, is designed, modeled, and evaluated in this work. The water circulation and heat extraction in the fractured reservoirs is modeled as a fully coupled process of fluid flow and heat transport. Using a newly developed, open-source, finite element based geothermal simulation code, FALCON, simulation results were obtained for a 30-year operation at a depth of 3 km and geothermal gradient of 65°C per km of depth. With a sensitivity study of the heat production to the design parameters, preferable fracture horizontal spacing, downward deviation angle of the parallel wells, and injection flow rate are recommended. Upscaling calculations of the developed EGS model have shown that, an industrial production-level system may be achievable if it consists of 40 equidistant fractures that connect two 1.2 km long parallel well sections with a well separation of 500 m; and if a system of these dimensions operates for 30 years at a flow rate of 0.1 m^3/s, with an electric power output at least 5 MW and pumping power of less than 1 MW. In particular, the performance metrics demonstrated in this work match well with those suggested by others, thus indicating the general applicability of our conceptual models.

1. Introduction

1.1. Heat extraction process in EGS

The concept of creating an engineered, or enhanced geothermal system (EGS) [3,11], first described as a hot dry rock (HDR) system in [12,30,31] and [13], originated at the Los Alamos National Laboratory (LANL) in the 1970s, and is of continuing interest due to the need for low CO_2-emission energy sources. Among the many aspects of EGS design, number and spacing of fractures, optimal placement of injection and production wells, flow rates and pressures, are all critical factors affecting heat production performance. However, largely due to the difficulty and expense of creating an EGS, many uncertainties exist regarding the optimal system design [35]. Numerical modeling and simulation methods provide one way of testing EGS design concepts, and incorporating much of the geometric complexity and complicated physics of those designs.

Based on the various conceptual designs of EGS well layout, the heat extraction process has been investigated extensively in recent years. The well layout schemes that are often modeled include three basic forms: 1) doublet (an injection and production well pair), 2) triplet (an injector flanked by a production well on each side), and 3) five-spot (an injector at the center and a production well at each corner of a square). Due to the great volume of literature published in this area, only some of the most recent works are reviewed here. Sanyal et al. [34] simulated a 30-year power generation period of a 3D hypothetical EGS model with a five-spot well layout, and analyzed the optimal performance of the model by performing a sensitivity study on fracture spacing, reservoir permeability, and well geometry. Zeng et al. [40] investigated the performance of a 2D conceptual EGS model with a horizontal doublet well layout, and concluded that the energy efficiency mainly depends on the reservoir permeability and the water production rate. Jiang et al. [17] designed and simulated a 40-year heat extraction period of a 3D conceptual EGS with a triplet well layout, and demonstrated that it is able to retain the preferential flow in

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List of symbols

c_w	Specific heat capacity of fluid $J \cdot kg^{-1} \cdot K^{-1}$
c_r	Specific heat capacity of rock $J \cdot kg^{-1} \cdot K^{-1}$
g	Magnitude of gravitational force $m \cdot s^{-2}$
K_m	Average thermal conductivity of the porous medium $W \cdot m^{-1} \cdot K^{-1}$
k	Reservoir intrinsic permeability m^2
Pe_h	Element Peclet number
p	Fluid pressure Pa
Q'	Thermal energy source/sink $J \cdot s^{-1}$
$\mathbf{q}$	Flux (Darcy velocity) vector $m \cdot s^{-1}$
s	Specific mass source/sink (or specific injection/ production rate) $kg \cdot m^{-3} \cdot s^{-1}$
T	Fluid temperature K
t	Time s
μ	Fluid viscosity $Pa \cdot s$
ρ	Fluid density $kg \cdot m^{-3}$
ρ_r	Rock density $kg \cdot m^{-3}$
ϕ	Reservoir porosity
∇	Vector differential operator m^{-1}

the reservoir and significantly elongate the heat production by 10 years over its doublet counterpart. Chen et al. [8] conducted a comparative study on the long-term performance between a doublet scheme, two triplet schemes, and a five-spot scheme for well layouts. Their results have showed that the performance of EGS could not be necessarily improved by simply deploying more production wells. Later on, Chen at al. [9] performed a detailed sensitivity study of design parameters for the EGS heat extraction process with a doublet well, and revealed that the heat extraction rate and lifetime of the system are tightly related to the flow pattern in the reservoir, while the thermal compensation from rocks surrounding the reservoir contributes little heat to the working fluid if the operation period is short. Though most of those works were based on hypothetical models that assumed isotropic and homogeneous subsurface environment, they have substantially advanced our understanding of how to optimize the long-term performance of the EGS heat extraction process.

1.2. Numerical modeling and simulation methods

Modeling the operation of an EGS plant requires reliable numerical methods to simulate the coupled thermal-hydraulic-mechanical (THM) processes. Nevertheless, the mechanical interaction between rock and fluid as well as the rock thermoelastic effect has been often neglected for simulating long-term EGS heat extraction process in many recent studies (with the reasons to be discussed later). For example, Zeng et al. [40,41] and Bujakowski et al. [7] used the finite difference method (FDM) based TOUGH2 code [28] for simulating the heat extraction process from EGS systems. However, FDM has a known disadvantage in that it requires high-quality structured meshes to obtain accurate solution, which could largely limit the complexity of the fracture features to be modeled. Though the FDM can also handle irregular meshes, the use of irregular meshes, in turn, could result in overly diffused solutions of convection-dominated heat transport in fractured reservoirs, which might lead to significantly inaccurate estimates of EGS design parameters. The inconvenience associated with FDM triggered the use of unstructured mesh based methods, such as the finite volume methods (FVMs) and finite element methods (FEMs). For example, based on the computational fluid dynamics (CFD) solver, Fluent® Jiang et al. [18] developed a 3D hydrothermal flow model that uses the cell-centered FVM for solving the transient incompressible flow and heat transfer with the Navier-Stokes equations in both the reservoirs and wells. It was then applied in an extensive study of EGS well layouts, for example, see [8] and [9]. However, it is not clear if their first-order FVM spatial discretization scheme was able to retain sufficient solution accuracy for long-term simulation of convective heat transport in fractured reservoirs. Alternatively, the Galerkin FEMs and so-called "Control-Volume" FEM (CV-FEM, nothing but the node-centered FVM) may offer more flexibility for reservoir modeling, as they support the implementation of 1D, 2D, and 3D elements in the same model (e.g., in a 3D EGS model, the fractures can be represented with 2D planar surfaces embedded in 3D rock matrix, and the wells can be represented with 1D curves). Examples include the "FEHM" code developed at LANL [42]; the "FRACTure" code by Kohl et al. [20] and applied by Held et al. [16]; and the "PANDAS" code by Xing et al. [39]. However, so far most of the FEM codes are not as powerful as the mature FDM code such as TOUGH2 to model some very complex problems, such as the coupled THMC processes (where "C" stands for chemical reactions). Further development of the FEM based numerical methods to overcome their existing weaknesses is in urgent demand.

1.3. Objectives and novelties

The objectives of the present work are to evaluate performance of several variants of a common conceptual EGS model. In this model, water is circulated through two parallel wells connected by a set of single large wing fractures in a fully saturated geothermal reservoir (see Fig. 1). The sensitivity of EGS heat production to some key design parameters, including the fracture horizontal spacing, flow rate, and well deviation angle, will be assessed, respectively. A newly developed, open-source FEM based geothermal simulation code, FALCON [36], has been used for the simulations. The novelty of this work is two-fold. First, a mixed-dimensional rock–fracture model is employed, where the fractures are represented using 2D planar domains that are embedded in a 3D domain that represents the surrounding rock matrix, with the same governing equations applied in both domains. Unlike the 2D single fracture model used in Refs. [40,41]; our 3D model takes into account the inter-fracture thermal interference, for which the long-term impact on the production wellbore temperature cannot be neglected where the fractures are spaced at reasonable distances. Second, this work considers a doublet parallel well layout with a downward deviation angle, and compares its performance to a similar system of horizontal wells. Third, open-source FALCON code used, and the simulation files for this study, are available to the public for continued development and/or testing of other scenarios.

The rest of this paper is organized as follows: Section 2 presents the governing equations for the coupled fluid flow and heat transport in geothermal reservoir environment, and constitutive models for calculating the density and viscosity of liquid-phase water. Section 3 describes the proposed 3D conceptual EGS model. Section 4 reports the numerical results of the simulation test cases and sensitivity analysis. Finally, Section 5 gives concluding remarks and outlook for future work.

2. Mathematical model

Initially introduced by Podgorney et al. [25]; our geothermal simulation code, FALCON, featured a parallel, fully implicit capability for modeling the fully coupled THM processes in a singly integrated code. FALCON has been developed using both pressure-