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Designing multi-well layout for enhanced geothermal system to better exploit hot dry rock geothermal energy

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Heat extraction mode, e.g. well layout or arrangement of wells, of enhanced or engineered geothermal system (EGS) is crucial to its performance and directly affects its commercial viability. Assuming the subsurface target hot dry rock (HDR) has been well-fractured and the created heat reservoir can be treated as a homogeneous porous medium, we numerically simulate the long-term heat extraction process of EGSs of various well layouts, including the standard doublet well layout, two triplet well layouts, and a quintuplet well layout. The simulation results enable a detailed analysis on the effects of well layout on EGS heat extraction performance. We find simply deploying more production wells does not necessarily improve the EGS heat extraction performance; an EGS with triplet well layout can perform better than an EGS with a quintuplet well layout or worse than an EGS with the standard doublet well layout. One more finding is an EGS with the injection well positioned close to the edge of the reservoir gets more thermal compensation from the un-fractured rocks surrounding the reservoir during heat extraction. Further, we deduce an optimized EGS well layout must ensure enough long major flow path and less preferential flow in the reservoir, and the injection well is located close to the edge of the reservoir. We then design a quartuplet well layout accordingly. Results from an additional simulation with respect to the quartuplet well EGS indicate its enhanced heat extraction performance, corroborating the success of design. Last, we discuss about the hot dry rock (HDR) heat recovery factor based on numerous simulated cases and estimate the amount of HDR geothermal resource that can be converted into electricity by EGS.

1. Introduction

There exists enormous heat in hot dry rocks (HDRs) beneath the planet. It was reported that the total HDR heat within subsurface 3–10 km depths of the United States (US) territory is more than 14×10^6 EJ [1]. A recent assessment conveyed that the storage of HDR heat within subsurface 3–10 km depths in China mainland is about 25×10^6 EJ [2]. Both are huge amounts compared with the total energy consumption in US or China, which is only about 100 EJ annually [1,2]. The HDR heat represents a large, indigenous energy resource that has the potential to provide base-load electric power with no or little environmental footprint [3]. Exploiting heat from HDR may be an important strategy to meet the fast-growing energy demand.

Research and development on the extraction and utilization of HDR heat started a few decades ago [1], dated back to the early 1970s when the concept of enhanced or engineered geothermal system (EGS) was first proposed by a group of US scientists. In the construction of EGS, a well is drilled to the target HDR and stimulation treatments are then performed to engineer the target HDR. After an artificial reservoir of adequate flow conductivity and sufficient heat exchange area is created, cold fluids are injected to flow through the reservoir. Heat stored in the HDR is transferred to the injected fluids and the heat-carrying hot fluids are harvested at the production well/wells. The outflow hot fluids are for earth-surface power-generation and/or direct heat utilizations. The exhaust fluids may be re-injected into the reservoir to form a circulation loop.

EGS has been widely envisaged as the major development direction of future geothermal energy utilization. Numerous projects [5–9] aimed at developing techniques for the creation of EGS pilot plants, have been and are still being conducted around the world.

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However, there is no an EGS plant that has been really commercialized to date. Designing advanced heat extraction modes (e.g. well layout or arrangement of wells) to efficiently mine heat from subsurface HDRs may improve the performance–cost ratio of EGS and accelerate its commercialization.

The procedures for constructing an EGS include geological investigation for site-picking, well-drilling, reservoir stimulation, construction of fluid-circulation system, construction of earth-surface power station, and installation of power transmission lines. Well-drilling is a requisite and the most costly procedure, as evident in many geothermal projects [1]. It was reported that the cost of well-drilling could amount to 50%–60% or more of the total capital investment [10,11]. The well-drilling technology is relatively mature as it has been developed and applied in the oil and gas industry for decades [12,13]. However, geothermal drilling, especially for applications in EGS, is often far more difficult than in the oil and gas operations as the HDR is usually harder and of higher temperature, and the fluids may be corrosive to the drill bit as well [10–14]. New technologies of borehole drilling are critically needed in the development of commercially viable EGS. A proper design of well layout may reduce technical risks at well-drilling and bring positive effects on the economic performance of EGS.

The single well productivity is a key factor dictating the commercial viability of EGS. An outflow of 80 kg/s flow rate with fluid temperature at 423.15 K or higher is the target for an EGS to achieve the goal of commercial operation [4]. No field tests have realized this target so far. The EGS project at Soultz has reported a maximum well productivity of about 26 kg/s [8]. To achieve sufficiently high well productivity remains to be a big challenge to the commercialization of EGS. The low circulation flow rate was mainly caused by the low permeability of the stimulated reservoir and the poor inter-well connectivity [15,16]. The multi-well strategy can add fracturing implementation loci, which is helpful in stimulating more fissures and somewhat homogenizes the distribution of permeability and porosity in the reservoir. Arranging more wells can generally shorten the well distance and can enhance the subsurface inter-well connectivity, facilitating the fluid circulation and at the same time reducing the possibility of fluid loss. Given the current rock fracturing technologies, the multi-well strategy may be one of the few effective methods to improve the well productivity. However, as aforementioned, the well-drilling is very time-consuming and costly. An optimal design to the well layout is absolutely needed before commencing practical well-drilling.

During the operation of an EGS, there undergoes a coupled thermal-hydraulic–mechanical–chemical (THMC) process in the subsurface fractured rock mass [17,18]. Nevertheless, the fluid flow and heat transfer (TH) process occurs in the subsurface region(s) of EGS play a pivotal role in the involved heat extraction process [19–21]. We have recently developed a 3D transient model, which is capable of modeling long-term heat extraction processes of EGSs [22,23]. This model focuses on the complete subsurface heat exchange (i.e. TH) process and safely neglects the chemical and mechanical (CM) actions between the rock and fluid.

The purpose of the present work is to scrutinize the effects of well layout on EGS heat extraction performance. We model the heat extraction processes of EGSs with various well layouts with the previous model [22,23]. The standard doublet (one injection well, one production well), two triplets (one injection well, two production wells) and a quintuplet (one injection well, four production wells) well EGSs are considered. Design and optimization of EGS well layout will be discussed accordingly. Moreover, we assess the recoverable HDR heat resource according to the overall heat extraction factor derived from a large quantity of model results.

2. Methodology

2.1. Model equations and concepts

We have previously reported a three-dimensional numerical model for the simulation of EGS long-term heat extraction processes [22,23]. In this model, the heat reservoir is treated as an equivalent porous medium characterized by some macroscopic properties (e.g. porosity and permeability) without considering any detailed information on fracture morphology and location. During the operation of EGS, the fluid injection temperature ranges from 300 to 350 K, evident temperature differences exist between the rock and heat transmission fluid in some portion or even most of the reservoir. The model considers local thermal non-equilibrium between the solid rock matrix and fluid flowing in the fractured rock, and employs two energy conservation equations to describe the temperature evolution of the rock matrix and of the heat transmission fluid in the fractures, respectively, enabling the modeling and analyses of local convective heat exchange in the reservoir. Another salient feature of this model is its capability of simulating the complete subsurface heat extraction process in EGS. The model treats the EGS subsurface multiple domains as a single-domain of three sub-regions associated with different sets of geophysical properties. Sub-region 1 represents the porous heat reservoir of finite porosity and permeability; sub-region 2 the impermeable solid rocks enclosing the heat reservoir; sub-region 3 the open-channel injection and production wells of unity porosity and infinite permeability. This single-domain treatment circumvents typical difficulties about matching boundary conditions between sub-domains in traditional multi-domain approaches and facilitates numerical implementation and simulation of the complete subsurface heat exchange process. The governing equations of this model are presented as follows.

Mass continuity equation:

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial\left(\rho\frac{\mathbf{u}}{\varepsilon}\right)}{\partial t} + \nabla\left(\rho\frac{\mathbf{u}}{\varepsilon}\cdot\frac{\mathbf{u}}{\varepsilon}\right) = -\nabla P + \nabla\cdot\mu^{\mathrm{eqv}}\nabla\frac{\mathbf{u}}{\varepsilon} - \frac{\mu}{K}\mathbf{u} + \rho\mathbf{g} \tag{2}$$

Energy conservation equation for the heat transmission fluid flowing in the fractures:

$$\frac{\partial\left[\varepsilon(\rho c_{\mathrm{p}})_{\mathrm{f}}T_{\mathrm{f}}\right]}{\partial t} + \mathbf{u}\cdot\nabla\left[(\rho c_{\mathrm{p}})_{\mathrm{f}}T_{\mathrm{f}}\right] = \nabla\cdot\left(k_{\mathrm{f}}^{\mathrm{eff}}\nabla T_{\mathrm{f}}\right) + ha(T_{\mathrm{s}} - T_{\mathrm{f}}) \tag{3}$$

Energy conservation equation for heat transport in the rock matrix of the heat reservoir or in the surrounding impermeable rocks:

$$\frac{\partial\left[(1-\varepsilon)(\rho c_{\mathrm{p}})_{\mathrm{s}}T_{\mathrm{s}}\right]}{\partial t} = \nabla\cdot\left(k_{\mathrm{s}}^{\mathrm{eff}}\nabla T_{\mathrm{s}}\right) - ha(T_{\mathrm{s}} - T_{\mathrm{f}}) \tag{4}$$

The application of the full-form Navier–Stokes momentum equation, Eq. (2), enables a general treatment to the fluid flow in open-channel injection and production wells and in the porous heat reservoir. Two energy equations, Eqs. (3) and (4) are used. One is for the heat conduction in HDR (or rock matrix); the other for the heat convection and advection in the fluid. In each of the energy equations there is a term $\pm ha(T_{\mathrm{s}} - T_{\mathrm{f}})$ introduced to describe the heat exchange between the solid rock matrix and fluid flowing in the fractures of the reservoir. The effective heat conductivities