



Parametric study of the production performance of an enhanced geothermal system: A case study at the Qiabuqia geothermal area, northeast Tibetan plateau

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ABSTRACT

Enhanced Geothermal System (EGS) is an essential approach to entrap heat from deep hot dry rock (HDR), a low-carbon and renewable energy. Understanding the long-term productivity performance of the EGS and its sensitivity to different reservoir parameters can help to achieve efficiently the optimized exploitation of a designated reservoir. The Qiabuqia geothermal area, located in the northeastern margin of the Gonghe basin, Tibetan Plateau, is one of the areas that have the greatest HDR geothermal resources exploration and development potential in China so far. Based on the geological data of the GR1 borehole at the Qiabuqia geothermal area, northeast Tibetan plateau, a 3D thermo-hydraulic coupled numerical model is established in this study with the method of finite element to assess the heat production potential. The mathematical model presented in this study is validated by the analytical solution of a single fracture model. By varying several key reservoir parameters (e.g. thermal conductivity, permeability, porosity, injection mass flow rate, injection fluid temperature, and lateral well spacing), the sensitivity analysis of the long-term production temperature and electric power rate evolution is implemented. The simulation results indicate that in the basal granitic reservoir with a depth of 2900 m–3400 m and a corresponding initial temperature of 160 °C–180 °C, the temperature produced and effective electric power can maintain at 173.4 °C and 2.48 MW for the first 7 years of simulation under the combination of 50 kg/s of injection flow rate, 60 °C of the injection fluid temperature and a 300 m of lateral well spacing. At the end of the 40-year operation period, the outlet temperature decrease to 162.8 °C, as well as a drop of 9.7% in the electric power. Sensitivity analysis with the method of ‘One Factor At a time’ suggests that the permeability is the parameter that affects the production temperature and energy extraction the most compared with the thermal conductivity and porosity. For a specified geothermal field with a known distribution of permeability, thermal conductivity and porosity, the injection mass flow rate has the most significant effect on the electric power output, followed by the injection temperature and the lateral well spacing. The results from the complete factorial experimental design simulation suggest the electric power performance of the reservoir can be increased by a reasonable multi-parameter combination. For a doublet well extraction system, based on the Qiabuqia geothermal area, a combination of 70 kg/s injection flow rate, 60 °C injection temperature, and 500 m lateral well spacing can attain an effective electric power output of 3.47–3.50 MW. Thus, this study compares the different heat mining performance potential under various reservoir parameters and their combinations through the aforementioned sensitivity analysis and can greatly promote the establishment and development of EGS program in the Qiabuqia geothermal area in the future.

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1. Introduction

1.1. Background

Geothermal energy is one of the most important low-carbon and renewable energy resource [1], which utilizes the heat generated in the interior of the Earth. Geothermal energy is continuously supplied by the decay of radioactive materials beneath the earth surface, heat transferred from the molten earth's core, as well as the heat absorbed from the sunlight [2]. In China, the total reserve of geothermal energy was estimated to be 3.06×10^{18} kWh/yr, which is equivalent to 7.9% of the total world's geothermal energy reserves [3]. According to the origins and condition of exploration, geothermal resources can be roughly divided into two categories: that is, traditional geothermal (hydrothermal) resource and hot dry rock (HDR) geothermal resource.

The conventionally hydrothermal geothermal resource, which is stored in the shallow depth beneath the earth surface, is generally in the form of thermal pools and hot springs and is commonly used for direct utilization like bathing, space heating and cooling, and some agricultural application [4]. The use of this kind of resource can be traced back to a few centuries ago in China. Preliminary result of the potential assessment of geothermal resources in China shown that the heat stored in the hydrothermal geothermal resource is about 2.5×10^4 EJ ($1\text{EJ} = 10^{18}\text{J}$) [5].

The HDR geothermal resource is another form of geothermal energy, which always stored in the rocks that have a sufficiently high temperature ($>150^\circ\text{C}$) but contain insufficient fluid owing to low porosity and permeability [6]. What attracts the interests of many countries around the world is their rich reserves, no CO₂ emission and stable natural resource [7,8] and the heat stored in HDR exceeds 90% of the total accessible geothermal energy [2]. The assessment study released by Wang et al. [5] suggested that the HDR resource within subsurface 3–10 km in China could reach 2.09×10^7 EJ, and mainly scattered in Qinghai-Tibet Plateau, West Yunnan (Tengchong), the southeast coast of China (Zhejiang, Fujian and Guangdong), Bohai Bay basin, Fenwei Graben in the southeast region of Ordos basin, and Songliao basin. If take 2% as the recoverable coefficient, the exploitable HDR energy in the depth range of 3–10 km was conservatively estimated to be 4.2×10^5 EJ, which approximately amounts to 4400 times the annual energy consumption of China in 2010 [5]. However, the exploitation and utilization of such a high-reserve geothermal resource are relatively slow compared with the hydrothermal resource. The main difference between the utilization of hydrothermal and HDR geothermal resources lies in that, for the HDR reservoir, a special reservoir rock stimulation process is needed to create an interconnected fracture network in a dense and nearly impermeable reservoir rock mass, e.g., granite. The enhanced geothermal system (EGS), which can create artificial heat reservoir and enhance the permeability of reservoir through the injection of pressurized liquid (typically water), has been successfully verified by the Fenton Hill HDR field test in America in the early 1970s [9,10]. During the last few decades, numerous countries including Japan, Germany, France, Australia, Switzerland, and Iceland have been devoted to the study of HDR resources development [11]. At present, the HDR and EGS researches in China as well as other countries are still in its infancy.

There is no doubt that EGS is an extremely complex, expensive and time-consuming geothermal energy utilization project, which mainly involves assessment of geothermal resources, drilling of injection and production boreholes, creation of artificial reservoir, microseismic monitoring, the water cycle between the injection and extraction boreholes for mining heat, power plant development, and maintenance of the reservoir and etc [12]. Numerical simulation method offers an economical and efficient way to

investigate and assess the production performance as well as environmental sustainability of a given EGS field before engagement. Thus, numerical simulation is gradually paid attention to by the researchers and reservoir engineers. Numerical simulation of energy extraction from the thermal reservoir originated in the 1970s and many literature on numerical simulation of EGS has been published in the past few decades. Bridsell and Robinson [13] conducted a three-dimensional model based on the data of the Fenton Hill HDR reservoir to study the impact on reservoir performance of redrilling the damaged production well. Magnenet et al. [14] studied the detailed reservoir temperature and pressure evolution of Soultz EGS site based on a two dimensional thermo-hydraulic-mechanical coupled model. Zeng et al. [15] investigated the heat performance potential of the Desert Peak geothermal filed by simulating the water circulation through a two horizontal wells. Feng et al. [16] made an electric production potential and investigate analysis of the Yangbajing geothermal field in Tibet, China. Liu et al. [17] investigated the heat extraction performance of the Zhacanggou geothermal field in Qinghai Province, China, under the influence of the altered CO₂ injection rate.

An accurate EGS simulation can not only provide valuable chances to understand the long-term geothermal energy extraction performance of the reservoir, but also offers useful information about the productivity effect of reservoir naturally occurring parameters (e.g. thermal conductivity, porosity, permeability) and human-controlled parameters, such as the well-doublet placement, injection mass flow rate and injection fluid temperature, which play crucial roles in a sustainable geothermal energy exploitation system.

In a simulation model, the quality and representative of the deep reservoir rock physical parameters determine the reliability of the simulation results. The uncertainties of the static formation temperature distribution (SFT), thermal conductivity, porosity and permeability of reservoir rock always lead to the deviation in the reservoir performance and affect the lifespan of the reservoir [18,19]. For example, the SFT distribution directly decides the total geothermal energy reserves in the reservoir and affect the lifespan of an EGS project, however, the SFT are difficult to acquire due to the drilling-induced transient disturbance (e.g. the circulation of drilling mud, the heat generated by the drilling tool) during the drilling process, and the downhole temperature logged by routine geophysical logging is generally lower than the SFT. Thus, it is necessary to measure the borehole temperature more than once to get the transient thermal recovery data temperature and then use some numerical simulators or analytical methods (e.g. Horner method, the spherical and radial heat-flow method, the cylindrical heat-source method) to estimate the SFT [20–24]. Except that, the thermal conductivity determines the heat transfer capacity of the reservoir rock. The higher thermal conductivity leads to faster heat conduction and more heat can be transferred from the hot rock to the injected low-temperature water [25]. However, it is very difficult to measure all the thermal conductivities for the entire reservoir domain. Thus, it is expected to rank the thermal conductivity values and then to evaluate the heat mining performance under the influence of different thermal conductivity values. Qu et al. [26] examined the effect of different fracture morphology on the heat mining performance. Zeng et al. [25] investigated the effect of the thermal conductivity, porosity and permeability on the reservoir productivity of the Yangbajing geothermal field in Tibet, China. Based on the geological data of the Soultz geothermal filed, Aliyu et al. [27] reported the effect of various combinations of thermal conductivity, porosity, and permeability on the production temperature.

Except for the reservoir naturally occurring parameters, the human-controlled parameters (i.e. the injection mass flow rate,

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