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Numerical simulation of electricity generation potential from fractured granite reservoir through vertical wells at Yangbajing geothermal field

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ABSTRACT

Yangbajing geothermal field is the first high-temperature hydrothermal convective geothermal system in China. Research and development of the deep fractured granite reservoir is of great importance for capacity expanding and sustaining of the ground power plant. The geological exploration found that there is a fractured granite heat reservoir at depth of 950–1350 m in well ZK4001 in the north of the geothermal field, with an average temperature of 248 °C and a pressure of 8.01–11.57 MPa. In this work, electricity generation potential and its dependent factors from this fractured granite reservoir by water circulating through vertical wells are numerically investigated. The results indicate that the vertical well system attains an electric power of 16.8–14.7 MW, a reservoir impedance of 0.29–0.46 MPa/(kg/s) and an energy efficiency of about 29.6–12.8 during an exploiting period of 50 years under reference conditions, showing good heat production performance. The main parameters affecting the electric power are water production rate and injection temperature. The main parameters affecting reservoir impedance are reservoir permeability, injection temperature and water production rate. The main parameters affecting the energy efficiency are reservoir permeability, injection temperature and water production rate. Higher reservoir permeability or more reasonable injection temperature or water production rate within certain ranges will be favorable for improving the electricity generation performance.

1. Introduction

1.1. Background

As the main body of geothermal resource, exploration and exploitation of the EGS (Enhanced Geothermal System) resource have received extensive attention all over the international energy sector [1,2]. Compared with other renewables, the EGS resource is more concentrated and stable, and can be used to generate base-load power with no need for storage and virtually no emissions [1–3]. In America, the EGS resource base within depth of 10 km is estimated to exceed 13 million exajoules (EJ, 1 EJ = 10^{18} J); of which 200000 EJ can be exploited under current technological conditions and this amounts to 2000 times the annual consumption of primary energy in the Unites States in 2005 [1]. Total EGS resource reserve in China within 3–10 km depth amounts to 20.90 M EJ; if we take 2% as the recoverable fraction, the recoverable EGS resource amounts to 4400 times total annual energy consumption in 2010 in China [4]. Influenced by collision and subduction from Indian Ocean plate, Philippine sea plate and Pacific plate to China's continental plate, huge potential high-temperature geothermal resource zone are formed at south Tibet, West Yunnan province, north Hainan province, Changbai Mountain and Wudalianchi district in China [3]. The most promising areas for EGS exploiting test are Yangbajing and Yangyi district in Dangxiong County in Tibet, Tengchong district in Yunnan Province and north Hainan Province [3–6].

The Yangbajing geothermal field is the first hydrothermal convective geothermal system of high-temperature in China, and the Yangbajing geothermal power plant has an installed capacity of 27.30 MW now from shallow hydrothermal reservoir. Yangbajing power plant has been running for more than 30 years and has accumulated abundant geological data and generation experience. However, after continuous exploiting for more than 30 years, the

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heat reservoir has obviously withdrawen, the land subsidence rate is accelerating, and the wellhead temperature, pressure and flow rate have all declined much. Now the shallow reservoir can only support 16 MW capacity, so development of deep high-temperature heat reservoir at this site has very important significance for capacity expanding and sustaining of the ground power plant [3,4,7–10]. Zeng et al. discussed fracture structures and structural model in detail of the Yangbajing geothermal field [11], and based on the consideration of overall costs of well drilling, reservoir stimulation and ground plant construction, Zeng et al. proposed that we should first exploit the heat resource of the 950–1350 m fractured granite reservoir [11]. Zeng et al. proposed the scheme of heat mining through one single horizontal well from the fractured reservoir, and conducted numerical simulation to reveal the electricity production characteristics and its dependent factors; the results indicate that the single horizontal well system attains an electric power of 3.23–3.48 MW and an energy efficiency of about 50.00–17.16 during 20 years, and this investigation is of great significance for guiding future exploration and exploitation of the deep high-temperature reservoir [11]. However, heat recovery efficiency of the single well system is very low because there is no circulating of cold water for heat mining [11]. Based on these findings, in this work we proposed to mine the heat by water circulating through vertical wells from the 950–1350 m fractured granite reservoir, and we also conducted the numerical investigation to reveal the heat production characteristics and its dependent factors through vertical wells.

In recent years, arrangement and design of wells in EGS have advanced much due to technology advance from oil and gas industry, and many new schemes of well arrangement and design have been applied [1,12]. Zeng et al. successively reported simulation results of heat production by water circulating through two horizontal wells and through two vertical wells at Desert Peak geothermal field, and heat production and electricity generation through one single horizontal well at Yangbajing geothermal field [11–14]. Sanyal et al. simulated the performance characteristics in detail of heat production through two vertical wells, three vertical wells and five vertical wells with double-porosity model, and the results indicate that only increasing reservoir permeability without increasing effective heat exchange area will have little effect on the heat production performance [15]. Watanabe et al. studied production performance of two vertical wells from supercritical high-temperature reservoir and found that changes of water viscosity and density along with temperature will have an important effect on the heat production performance [16]. Shaik et al. simulated the fluid-rock coupling heat transfer in naturally fractured geothermal reservoir, and found that the commonly used heat transfer approaches will underestimate the production temperature when applied to the naturally fractured geothermal reservoirs [17]. Vörös et al. investigated the exploiting potential of EGS at Cooper Basin of Australia and found that well arrangements of hexagonal pattern and square pattern don't show significant differences in the system thermal behavior, while the dominant parameter affecting the long-term thermal performance is well separation [18]. Pashkevich et al. studied the thermal performance of magma-geothermal system of Mutnovsky volcano, a typical supercritical EGS using porous media model and found that well rate, production zone permeability, relative height injector bottom above of the producer bottom, and well separation all influence the production performance of supercritical EGS [19]. Pruess, Spycher and Borgia et al. respectively investigated advantages of CO_2 as working fluid of EGS instead of water and interactions between CO_2 and rock within EGS reservoirs [20–22]. These studies are of great importance for promoting future research and development of EGS all over the world.

1.2. Research objectives

This investigation aims to study the heat production and electricity generation characteristics from the 950–1350 m fractured granite reservoir by water circulating through vertical wells at well ZK4001 at Yangbajing geothermal field, and to determine the conditions under which profitable field production could be realized. This work is of great significance for promoting future exploration and exploitation of deep high-temperature reservoir at Yangbajing geothermal field.

The novelty of this study mainly lies in three features. First, the scheme of heat mining and electricity generation by water circulating through vertical wells from deep fractured granite reservoir is proposed. Second, the compressible flow model is adopted, the influence of temperature and pressure on water viscosity and density is taken into consideration, and the influence of water density on energy efficiency is also analyzed. Third, the conceptual model is established based on the real geological background at Yangbajing geothermal field, and the research conclusions are more practical for engineering applications.

2. Production method and well description

2.1. Fractured reservoir stimulation and design

The microfracture in the hot rock can be stimulated by hydrofracture, explosion or chemical action to enlarge porosity and permeability of the fracture network, and through these an EGS reservoir can be created in hot rock [1,23–26]; this process is termed as reservoir stimulation and it is core technology of EGS. Through reservoir stimulation an EGS reservoir can be constructed in hot dry rock, and effective volume and average fracture spacing of the reservoir are indicators that represent the production performance of the EGS reservoir. The effective volume determines the amount of in site heat that can be mined, while the average fracture spacing determines the heat transfer area between the fluid and solid rock, and also determines heat production rate to a great extent. Within certain ranges greater effective volume and smaller average fracture spacing will be favorable for improving the heat production performance and efficiency [24,27]. The effective volumes of reservoir from field tests have reached more than 2 km^3 [1], and the average fracture spacing from filed tests have enlarged from 0.33 m to 300 m [15]. The effective volume of commercial EGS reservoir should be larger than 2×10^8 m^3, and the effective heat transfer area should be larger than 2×10^6 m^2 [23]. There have already been many natural fractures in the deep 950–1350 m fractured granite reservoir, and reservoir permeability is within 1–25 mD (1 mD = 1.0×10^{-15} m^2); there is also natural water in the fractured reservoir, so there is no need for stimulation or only need for low pressure stimulation [11]. Neglecting water recharge from deep formation, the 950–1350 m reservoir is composed of an impermeable cap rock, a permeable granite reservoir and an

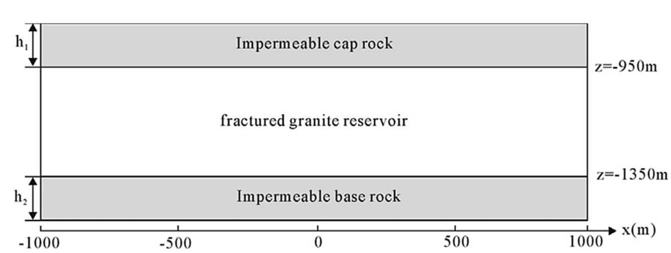

Fig. 1. Conceptual model of the 950–1350 m fractured granite reservoir at Yangbajing geothermal field [11].