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Research Paper

Numerical investigation of electricity generation potential from fractured granite reservoir by water circulating through three horizontal wells at Yangbajing geothermal field

Yuchao Zeng[a], Jiemin Zhan[a,*], Nengyou Wu[b], Yingying Luo[a], Wenhao Cai[a]

[a] School of Engineering, Sun Yat-sen University, Guangzhou 510275, China
[b] Qingdao Institute of Marine Geology, China Geological Survey, Qingdao 266071, China

HIGHLIGHTS

- A numerical model of the 950–1350 m fractured granite reservoir through horizontal wells is established.
- Desirable electricity production performance can be obtained under suitable conditions.
- The system attains an electric power of 26.9–24.3 MW with an efficiency of about 50.10–22.39.
- Electric power mainly depends on water production rate and injection temperature.
- Higher permeability within a certain range is favorable for electricity generation.

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ABSTRACT

Deep geological exploration indicates that there is a high-temperature fractured granite reservoir at depth of 950–1350 m in well ZK4001 in the north of Yangbajing geothermal field, with an average temperature of 248 °C and a pressure within 8.01–11.57 MPa. In this work, we evaluated electricity generation potential from this fractured granite reservoir by water circulating through three horizontal wells, and analyzed main factors affecting the performance and efficiency through numerical simulation. The results show that in the reference case the system attains a production temperature of 248.0–235.7 °C, an electrical power of 26.9–24.3 MW, an injection pressure of 10.48–12.94 MPa, a reservoir impedance of 0.07–0.10 MPa/(kg/s), a pump power of 0.54–1.08 MW and an energy efficiency of 50.10–22.39 during a period of 20 years, displaying favorable production performance. Main factors affecting the production performance and efficiency are reservoir permeability, water production rate and injection temperature; within certain ranges increasing the reservoir permeability or adopting more reasonable water production rate or injection temperature will obviously improve the system production performance.

1. Introduction

1.1. Background

Under the pressure of energy shortage and environment pollution, research and development of renewable and clean energy have received worldwide attention. Enhanced geothermal system (EGS) is an engineered system which adopts artificial circulating water through underground fractured hot dry rock (HDR) in depth of 3–10 km to economically extract the geothermal energy, and it is one of main study areas of geothermal energy in the future [1]. Compared with other renewable, the EGS resource is more concentrated and stable, can be used to generate base-load power with no need for storage and virtually no emissions, so recently the research and development of EGS have received wide attention [2–5]. In America, total EGS resource reserve within 3–10 km depth amounts to 14×10^6 EJ ($1 \text{E J} = 10^{18}$ J); if we take 2% as the recoverable fraction, the recoverable EGS resource amounts to 2.8×10^5 EJ and it is 2800 times total annual energy consumption in 2005 in the USA [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 [2]. It is predicted that EGS will provide about 100,000 MW electric power

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* Corresponding author.
E-mail address: cejmzhan@gmail.com (J. Zhan).

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Nomenclature

g	gravity, 9.80 m/s^2
h	well depth, m
H_1	thickness of cap rock, m
H_2	thickness of bottom rock, m
h_1	depth of injection well, m
h_2	depth of production well, m
h_{inj}	injection specific enthalpy, kJ/kg
h_{pro}	production specific enthalpy, kJ/kg
I_R	reservoir impedance, MPa/(kg/s)
k	reservoir permeability, m^2
k_x	intrinsic permeability along x, m^2
k_y	intrinsic permeability along y, m^2
k_z	intrinsic permeability along z, m^2
P	pressure, MPa
P_c	critical pressure, MPa
P_{inj}	injection pressure, MPa
P_{pro}	production pressure, MPa
P_0	bottomhole production pressure, MPa
q	water production rate, kg/s
Q	total water production rate, kg/s
T	temperature, °C
T_{inj}	injection temperature, °C
T_0	mean heat rejection temperature, 282.15 K
T_{pro}	production temperature, °C
W_{h}	thermal power, MW
W_{p}	electric power of pump, MW
W_{e}	electric power, MW
x, y, z	cartesian coordinates, m
ϕ	reservoir porosity
η	energy efficiency
η_{p}	pump efficiency, 80%
ρ	water density, kg/m^3
λ	rock heat conductivity, W/(m K)

by 2050 in the USA, occupying about 10% of total electricity generating capacity [1].

The research and development of EGS mainly includes two aspects: field tests and numerical simulations [1]. Since the pioneering field test work of EGS of the Los Alamos National Laboratory at Fenton Hill in 1974, main developed countries in the world have conducted many engineering projects, trying to prove effectiveness of the EGS technologies [1]. So far, we have long been able to drill the wells, stimulate the rock to improve transmissivity, target wells into the stimulated volume and make a connection between producer and injector. We can circulate the fluids for long time period at reasonably high rate, 10–30 kg/s. The field tests have proved that the reservoir stimulation is through shearing of pre-existing fractures; fractures that are stimulated are those that will take fluid during pre-stimulation injection; the first well needs to be drilled and stimulated in order to design the entire system; rock–fluid interaction may have a long-term effect on reservoir operation [1].Three major issues remained at the end of the project as constraints to commercialization: (1) the demonstration of sufficient reservoir productivity with high-productivity fracture systems of sufficient size and thermal lifetime to maintain economic fluid production rates, (2) the maintenance of these flow rates with sufficiently low pumping pressures, and (3) the relatively high cost of drilling deep wells in hard rock [1].

Because filed tests of EGS are expensive, time-consuming and greatly difficult, numerical simulations of EGS have made great progress in recent years [6–10]. There are two key issues in modeling an EGS reservoir, one is to properly characterize and simplify the practical complex fracture system, and the other is to reasonably simplify and dispose the coupling effect among fluid mechanical, rock mechanical, hydraulic, thermal and chemical processes within the reservoir [6–10]. There are mainly two methods to characterize the fracture: equivalent continuous porous medium and real discrete fracture network [6–10]. The equivalent continuous porous method will regard the discrete fracture system as continuous porous media, such as the equivalent porous media (EPM) or the effective continuum method (ECM), the double-porosity method (DPM), and the multiple interacting continua (MINC) method [4–7]. The discrete fracture network (DFN) model will analyze the fracture orientation, size, spacing and other mechanical properties to establish a fracture network model. For the coupling effect in the thermal–hydrologic–mechanical–chemical processes, key points are the coupling between fluid flow and heat transfer, and the coupling between the fluid flow, heat transfer and rock deformation; studies dealing with the coupling associated with chemical interaction are increasing in recent years [6–10].

Zeng et al. used the EPM method to analyze the performance and efficiency of two horizontal wells at Desert Peak geothermal field and found that the system attains an electrical power of 8.6–6.2 MW and an energy efficiency of 30.6–10.8 [4]. McDermott et al. used the EPM method to investigate impacts of the coupling interaction of thermal–hydrologic–mechanical–chemical processes on the heat production performance of EGS, and found that under different conditions regarding different coupling processes, the thermal power is minimum when water properties are functions of temperature, pressure and salinity while rock properties are constant [11]. Sanyal et al. used the DPM to analyze the electricity generation perspective of EGS, and fount that cooling rate, net generation profile versus time and reservoir heat recovery factor are the most appropriate criteria indicating performance of EGS; only increasing reservoir permeability without changing the average fracture spacing will result in very slight effect on the electrical power [12]. Gelet et al. used the DPM to study the performance of EGS reservoirs in local thermal non-equilibrium, and found that when the average facture spacing is small the single porosity model can attain good simulation results, while for large average fracture spacing the DPM method is more reasonable [13]. Pruess, Spycher and Borgia et al. respectively used the MINC to investigate advantages of CO_2 as working fluid of EGS instead of water and interactions between CO_2 and rock within EGS reservoirs [14–17]. If the data of reservoir fracture distribution are adequate, the DFN model can be adopted [4]. Jing et al. adopted the stochastic DFN to research the heat production performance of EGS, and found that rock thermoelasticity has significant effect on the production temperature, injection pressure and water loss [18]. Kolditz et al. used the DFN to investigate the performance characteristics of Rosemanowes EGS, and found that compared with single or multiple parallel fracture models the DFN model is more reliable [19].

So far, most wells of both actual and conceptual EGSs are vertical or sub-vertical, and reports on horizontal wells in EGSs are rare [1,20]. Field tests indicate that the minimum principal stress of subsurface formation is generally horizontal, so the shearing failure or dilation of natural joints principally generates vertical or sub-vertical fractures, and the best approach to connecting the discrete vertical fractures is by horizontal well [1,5,20]. During the