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Analysis of influencing factors of production performance of enhanced geothermal system: A case study at Yangbajing geothermal field

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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 established a conceptual and numerical model of this granite reservoir, evaluated heat production and electricity generation potential from this fractured reservoir by means of numerical simulation, and analyzed main factors affecting the heat production performance. The results indicate that in the reference case the system attains an electric power of 29.5–25.1 MW, a reservoir impedance of 0.12–0.21MPa/(kg/s), a pump power of 0.7–1.6 MW and an energy efficiency of 41.1–15.7 during a 50 year period. Main factors affecting the electric power are water production rate and injection temperature. Main factors affecting the reservoir impedance are the reservoir permeability, the water production rate and the injection temperature. Main factors affecting the pump power are the reservoir permeability, the water production rate and the injection temperature. Main factors affecting the energy efficiency are the reservoir permeability, the water production rate and the injection temperature. Within certain ranges main measures to improve the reservoir performance are to increase the reservoir permeability or adopt more reasonable water production rate and injection temperature.

1. Introduction

1.1. Background

Enhanced geothermal system (EGS) resource is the part of greatest potential of geothermal energy, and total EGS resource within 10 km depth that can be exploited occupies more than 90% of the geothermal resource [1]. Total EGS resource within 10 km depth all over the world amounts to about 40–400 M EJ (1EJ = 10^{18}J), approximately 100–1000 times the quantity of fossil energy [2]. Compared with other renewable, the EGS resource is more concentrated and stable, very suitable for generating base-load electric power, with a high utilization efficiency and nearly no pollution emission [1,3]. In America, the EGS resource base within depth of 10 km is estimated to exceed 13 million exajoules (EJ); of which 200000EJ 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 168 times the quality of traditional hydrothermal resource or 4400 times total annual energy consumption in 2010 in China [4]. It is predicted that there will form commercial exploitation of EGS in the next 15 years, human will large-scalely utilize EGS to generate electricity by 2030, and EGS will provide about 100000 MW electric power by 2050 in the USA, occupying about 10% of total electricity generating capacity [1].

Because filed tests of EGS are expensive, time-consuming and greatly difficult, numerical simulation plays a major role in the study area of performance analysis of EGS, and under this condition numerical studies of EGS have made great progresses in recent years [5–9]. Accurate simulations of EGS reservoir need considerations of two aspects: to characterize the fracture and to simplify the interaction of multi-physical fields of thermal-hydrologic-mechanical-chemical processes [6,7]. There are mainly two

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methods to characterize the fracture: equivalent continuous porous medium and real discrete fracture network [6,7]. The former will treat the real discrete fractures as an equivalent continuous porous medium and greatly simplify the calculation, such as the equivalent porous media (EPM) method or the effective continuum method (ECM), the double-porosity method (DPM) and the multiple interacting continua (MINC) method [6,7,10,11]. The latter will analyze the fracture orientation, size, spacing and other mechanical properties to establish a discrete fracture network (DFN) model [7,8]. For the coupling effects, the coupling between fluid flow and heat transfer is most important, and reports of couplings among the fluid flow, heat transfer and mechanical deformation or couplings among the fluid flow, heat transfer and chemical reaction are increasing in recent years. The coupling models are in continuous improvement, but they are not widely applied to the practical engineerings [8].

The EPM is mainly used to model densely fractured reservoir of which fracture density is high and fracture spacing is small, normally the average fracture spacing is less than 2~3 m, because under this condition the assumption of instantaneous local thermal equilibrium between matrix and fracture is valid [5,7,12,13]. Birdsell et al. used the EPM to study the process of fluid flow, heat transfer and tracer migration in Fenton Hill EGS reservoir, and found that the water viscosity in the reservoir gradually increases and this results in the increase of reservoir impedance [14]. McDermott et al. used the EPM 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 [15]. Watanabe et al. used the EPM to analyze uncertainty of thermal-hydrologic-mechanical coupled processes in EGS reservoir, and demonstrates the importance of taking parameter uncertainties into account for geothermal reservoir evaluation in order to assess the viability of numerical modeling [16]. Zeng et al. used the EPM to evaluate the heat production potential and efficiency of two horizontal well system at Desert Peak geothermal field, and found that the system attains an electric power of 8.6–6.2 MW during a period of 20 years [17]. When the average fracture spacing is higher than 10 m, the temperature difference between rock and water must be taken into consideration, and the DPM or MINC method is more reasonable [5,8,10,11]. 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 [18]. Taron et al. used the DPM to study the thermal-hydrologic-mechanical-chemical processes in the evolution of engineered geothermal reservoirs, and found that in most of the reservoir, cooling enhances permeability and increases fluid circulation under pressure-drive [19,20]. Gelet et al. used the DPM to study the performance of EGS reservoirs in local thermal non-equilibrium [21,22]. 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 [23–26]. If the data of reservoir fracture distribution are adequate, the DFN model can be adopted. Baujard et al. used the DFN to research the influence of water density on pressure distribution and stimulated volume in EGS reservoir [27]. Kolditz et al. used the DFN to investigate the performance characteristics of Rosemanowes EGS, and successfully predicted the long-term production performance [28,29]. 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 [30–32].

We can develop different kinds of EGS reservoir model regarding different coupling effects of thermal-hydrologic-mechanical-chemical processes, and there have been preliminary understandings on influences of rock deformation and chemical reaction on the heat production performance [6–8]. While the enhancement of fractures with time due to thermal contraction of the rock is possible, gradual closing of fractures or degradation of fractures due to scaling is equally possible [18]. Therefore, we can simultaneously neglect the effects of rock deformation and chemical reaction and just assume that after stimulation the fracture aperture and spacing remain unchanged over the heat production lifetime [18]. The injected cold water will arouse rock contraction, and this will increase the fracture aperture and decrease the reservoir impedance [33]. Although fluid loss from the fracture into the matrix reduces the pressure in the fracture, the poroelastic stress associated with fluid leak-off tends to reduce the aperture and increase the pressure in the fracture. High rock stiffness and low fluid diffusivity cause the poroelastic contraction of the fracture aperture to slowly develop in time. The maximum reduction of aperture occurs at the injection well and become negligible near the production well [34]. Thermally induced stress increases the fracture aperture near the injection well, and the fluid pressure at the injection well is greatly reduced. The thermoelastic effects are particularly dominant near the inlet compared to those of poroelasticity, but are pronounced everywhere along the fracture for large times [34]. The mechanical deformation effect of reservoir rock will increase the thermal power, and the thermal power will greatly improve if the rock deformation is taken into consideration [15]. The injected cold water will cause excessive contraction of part fractures, the heterogeneity of reservoir rock and fluid properties will arouse the formation of preferential flow, and these may short-circuit the circulating water [15,33,35]. In a hot system, the cooling would produce significant contraction of the rock around the flow path. This in turn would tend to increase the aperture of the fracture resulting in more and more flow being channeled along the cold path and this kind of positive feedback will finally result in the development of short circuit [36]. The strong influence of initial condition on the thermal drawdown emphasizes the importance of correct initial conditions for complicated reservoir models [28]. The increase of well spacing will significantly slow down the drawdown of production temperature and improve the thermal power [29]. Fluid chemistry, initial rock temperature, magnitude of flow rate and well spacing have a major effect on water/rock chemical interaction (WRCI), and for a multi-well geothermal system, WRCI seems to make the flow distribution tend towards uniformity [31]. WRCI has little effect on flow rate and production drawdown, unless the initial rock temperature assumed to increase to 300 °C, WRCI may cause a permeability enhancement that could lead to an increased flow rate [31]. A large improvement in the long-term performance of the Hijiori reservoir could result from increasing well spacing from 100 m to 150 m without major degradation of the hydraulic performance [30]. In the view of long-term production performance of EGS, the studies demonstrate the strong influence of mechanical effects in the short-term, the influence of thermal effects in the intermediate term and the prolonged and long-term influence of chemical effects, especially close to injection [20].

Although we have made great progresses in the area of fracture characterization and multi-physical field coupling presentation, there are general drawbacks of current EGS reservoir models. First, currently most EGS models only consider the production temperature profile as the indicator of production performance, while generation profile versus time and energy efficiency profile versus time are also the most appropriate criteria [18]. Second, nearly all the current EGS models neglect analysis of injection pressure and