Renewable Energy 126 (2018) 107–125

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Experimental investigation of granite properties under different temperatures and pressures and numerical analysis of damage effect in enhanced geothermal system

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ARTICLE INFO

Article history:
Received 18 September 2017
Received in revised form
21 February 2018
Accepted 26 February 2018
Available online 27 February 2018

Keywords:
Enhanced geothermal system
Hot dry rock
triaxial test
Reservoir damage
Reservoir simulation

ABSTRACT

In this work, the variation in granite mechanical property with temperature (30 °C–150 °C) under different confining stresses (0.1–60 MPa) is experimentally investigated specifically for reservoir secondary damage of hot dry rock through a series of triaxial tests. On the basis of the test results, the damage equations of elastic modulus and Poisson's ratio of granite are obtained in accordance with damage theory. These equations are programmed into the TOUGHREACT-FLAC3D software. A field scale simulation is conducted to analyze the effect of secondary damage on the final generated electricity. The results indicated that as temperature and confining pressure gradually increase, the expansion direction of fracture turns from vertical to oblique and decreases to a single fracture plane. The mechanical properties of rock are continuously weakened with the increase in temperature. The confining pressure exerts a positive influence on elastic modulus and Poisson's ratio of granite. The rock property around the discharge section of injection well is damaged significantly and is fractured because of the high temperature difference. The reservoir secondary damage decreases the reservoir temperature gradually, thereby reducing the generated power.

1. Introduction

Geothermal technologies use the naturally occurring heat located in shallow ground, hot water and rock below the earth's surface to generate electricity. Geothermal is considered a renewable source of energy because the earth's core generates nearly unlimited heat [1]. With current geothermal technologies, electricity can be generated only where three key conditions are met: heat, fluid and natural permeability at depth. Small underground pathways conduct fluids through the hot rocks, carrying energy in the form of heat through wells to Earth's surface, driving turbines and generating electricity.

Breakthrough technology called Enhanced Geothermal System (EGS) can generate electricity anywhere there is hot rock at depth, greatly expanding the potential for geothermal power [1]. EGS are man-made reservoirs created by drilling wells thousands of feet below the earth to access hot rock at the earth's crust. Highly pressurized cold water is pumped through the wells to cause pre-existing fractures of the hot rock to open up, increasing permeability. This enables the water to flow through the cracked rock and pick up heat. The resulting hot water pumps back to the surface where it is depressurized to make steam, which spins a turbine to generate electricity. The water is then cooled and pumped through the wells again, repeating the same process and creating a closed-loop system.

Reservoir stimulation and thermal extraction (through water circulation between wells and hot reservoir) are two of the most critical technologies of EGS. The lifetime of an EGS project is generally designed for at least 20 years [1]. During such a long water circulation period, the continuous injection of cold water moves the cold front surface from the injection well toward the production well every year through the hot reservoir. Given that rock inherently contains micropores and microcracks, the mechanical properties of rock (e.g., elastic modulus and Poisson's ratio) are not immutable but vary with the change in environment (e.g., temperature and pressure) [2,3]. Therefore, the reservoir rock

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https://doi.org/10.1016/j.renene.2018.02.117
0960-1481/

Nomenclature

E	young's modulus, MPa
G	shear modulus, MPa
K	permeability, D
P_{inj}	injection pressure, MPa
W_e	electrical power, MW
ρ	density, kg/m^3
v	poisson's ratio
n	porosity
σ	stress, MPa
σ_V	vertical stress, MPa
σ_H	maximum horizontal stress, MPa
σ_h	minimum horizontal stress, MPa
ε	strain
D	darcy (1 D = 9.869233 × 10^{-13} m^2)
inj	injection
max	maximum
min	minimum
pro	production

properties of EGS will change and secondary failure will occur during a long lifetime [1,4]. These phenomena will change the reservoir scale, thereby influencing the temperature and seepage fields of the reservoir. As a result, the amount of generated electricity will be affected. Thus, the change rule of rock mechanical property with temperature and pressure should be investigated for the development of EGS.

When rocks are under high temperature and high pressure, the mechanical properties are different from those at room temperature. The mechanical parameters obtained at room temperature cannot be utilized to analyze and then guide the deep engineering works of EGS. Hence, it is imperative to measure the mechanical parameters of rocks under high temperature and high pressure. Rock damage under load and temperature change has been intensively studied experimentally and theoretically.

A large number of laboratory experiments have been conducted to investigate the influence of high pressure and temperature on rock [5,6]. The elastic modulus, Poisson's ratio, tensile strength and uniaxial compressive strength of sandstone [7,8], granite [9,10], marble [11,12] and limestone [13,14] decrease with the increase of temperature. For sandstone and granite, the quartz mineral transformation phase is reached at 573 °C, which leads to the dramatic weakening of their mechanical properties [5,15]. Similarly, calcium carbonate decomposes at 800 °C, which results in the dramatic weakening of the mechanical properties of marble and limestone [5]. From 0 to 200 °C, depending on the rock type and the heat treatment method, the Poisson's ratio and the internal friction angle change with the increase of temperature [8,14]. The cohesion decreases with increasing temperature, and it decreases dramatically after the critical temperature point [8]. The elastic modulus of sandstone increases at first and then decreases with the temperature increasing to 800 °C [7]. The external factors, natural fractures and the free water content in rocks influence the thermal expansion coefficient. Since the thermal expansion coefficient is different for different parts of rock, new fractures occur. The temperature also has a prominent influence on the heat conductivity coefficient of rocks. Specifically, it decreases according to an approximately inverse proportional function with increasing temperature [5]. Increasing the temperature leads to reduction in the failure stress of rock under any confining pressure. The reductions of strength characteristics are relatively small up to 500 °C and beyond that an accelerated down-ward trend are identified [16].

Rock is a natural material with a few initial defects, such as microcracks; thus, damage theory is an effective method for studying its property evolution [17]. Wang et al. proposed a statistical damage constitutive model of rock softening using the Weibull distribution based on the intensity of the mesoscopic unit to describe the entire continuous process of microcracks from injury to fracture [18]. Graham-Brady built an elastic damage model based on fracture mechanic theory, and this model can be used to describe the stress–strain relationship of the single axial compression of rock material [19]. Yin et al. established the rock damage constitutive equation by considering temperature effect based on endochronic theory [20]. Zhang et al. experimentally investigated the variation in the mechanical properties of granite with temperature and time [21]. Fang et al. studied the thermal elastic–plastic properties of rocks under high temperature [22]. Xu presented the constitutive equation of a one-dimensional, thermal-mechanical coupled elastic thermal damage by referring to the Lemaitre damage model [23]. Yan and Zheng built a coupled thermo-mechanical model for simulating the thermal cracking of rock based on a combined finite–discrete element method [2]. Xia et al. proposed a thermo-mechanical coupling particle model for simulating thermally induced rock damage based on the particle simulation method [24].

The above research indicates that, the mechanical properties of rocks are continuously weakened with the increase in temperature. The specific performance is generally brittleness weakening and plasticity enhancing. The thermal damage mechanism can be divided into three stages: (1) when heating temperature is low (approximately <200 °C), the rupture of rock is developed in the form of propagating microcracks because of the differences between the thermal expansion coefficient of rock minerals and the existence of "original defects" (e.g., microcracks and microvoids). This situation is generally reversible; (2) when temperature continues to increase (approximately 200 °C–800 °C), the water in the mineral structure of rock evaporates and dissects, thereby leading to a gradual "intergranular fracture"; (3) when temperature is sufficiently high (approximately >800 °C), chemical reactions will occur inside rock minerals and relevant organic matter will be precipitated. Different rocks possess dissimilar temperature thresholds.

However, the previous studies were conducted at wider temperature ranges (up to 800 °C) and the researchers therefore did not pay close attention to reservoir rock behavior under relatively low geothermal temperature ranges (<150 °C). Additionally, there are few works about the effects of rock mechanical damage on the EGS capacity during its long-term lifetime. This was the focus of the present study. For the current EGS projects, the thermal damage and the creation of microcracks of EGS reservoir rock during the operation period are presumed to mainly belong to the above-mentioned stage (1) given that the reservoir temperature is generally approximately 200 °C. In the deep, high-temperature, and high-stress environment, the injected cold water will cause shrinkage stress among the rock particles because the thermal expansion characteristics of different mineral grains are different. When the surrounding rock cools to a certain temperature, the shrinkage stress inside the rock will exceed the tensile yield strength of the rock, thereby damaging or breaking the rock. Porosity, permeability, elastic modulus, and Poisson's ratio will also change. Therefore, in this study, based on the real geological conditions of a potential hot dry rock reservoir in China, the influence of rock damage on reservoir heat transfer during 20 years was evaluated. The reservoir is located in the depths of −4000 m (about 153 °C, igneous rock) [25]. First, we investigated the variation in granite mechanical property with temperature (30 °C–150 °C)