Energy 162 (2018) 630–644

Contents lists available at ScienceDirect

Energy

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

A novel single-well geothermal system for hot dry rock geothermal energy exploitation

Wenbo Huang, Wenjiong Cao, Fangming Jiang*

Laboratory of Advanced Energy Systems, Guangdong Key Laboratory of New and Renewable Energy Research and Development, CAS Key Laboratory of Renewable Energy, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (CAS), Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 30 September 2017
Received in revised form
30 July 2018
Accepted 7 August 2018

Keywords:
Hot dry rock
Enhanced geothermal system
Supercritical CO_2
Earth-deep geothermal energy
Downhole heat exchanger
Heat pipe

ABSTRACT

Existing hot dry rock geothermal projects are commonly confronted with some technical issues, such as corrosion and scaling, and water loss. To resolve these issues, the present work proposes a novel system for mining hot dry rock geothermal energy, in which a reservoir is combined with a heat pipe system. The new system encompasses a heat pipe placed in a single-well to extract hot dry rock geothermal energy, while an artificial reservoir is built around the main endothermic region of the well, which is permeable and saturated with carbon dioxide (CO_2). This wellbore structure design may stimulate a stronger natural convection in the reservoir, resulting in a higher thermal power production. To evaluate the proposed system, an extensive numerical investigation was conducted. The comparison of the proposed system with the conventional downhole heat exchanger (DHE) system in terms of heat extraction performance indicates clear superiority of the proposed system primarily due to the associated thermosyphon effect of CO_2 fluid in the reservoir. To better understand how operating and design variables affect the heat extraction performance of the system, a detailed sensitivity analysis was conducted taking into consideration a wide range of possible configurations and working conditions. The eventually obtained knowledge will guide the design of the system in practice.

1. Introduction

Geothermal energy is an important branch of the so-called renewable energies and it is typically characterized by good reliability due to its lack of dependence on the weather condition, which is a major advantage, in particular, for electricity power generation. The World Energy Assessment (WEA) estimates that global annual potential of available geothermal energy is about 600,000 EJ [1]. Considering the present annual global energy consumption is about 570 EJ [2], geothermal energy is practically an infinite energy resource. Present exploitation of geothermal energy falls primarily into the hydrothermal resource category, in which natural fracture networks contain a fluid and allow its circulation. The requirement of a particular type of geologic structures restricts the construction of hydrothermal electricity power stations to a limited number of regions in the world.

Hot dry rock (HDR) energy is another form of geothermal energy, representing a vast store of thermal energy that is contained in the hot impervious crystalline basement rocks. Investigation shows more than 90% of the total US geothermal resource is stored in HDR [3]. Aiming to extract the energy stored in HDR, the prototype of an Enhanced Geothermal System (EGS) was designed and implemented by the Los Alamos National Laboratory in the 1970s [4]. The initial concept is straightforward: for low-permeability rocks, a series of rock-fracturing procedures, such as hydraulic stimulation to create an artificially fractured reservoir is performed. By circulating water through the stimulated region, heat can be continuously extracted from the rock, just like a natural hydrothermal system. EGS has drawn a considerable amount of interest over the past 40 years. However, so far significant financial risks still exist for EGS projects since it remain as a major challenge to effectively control the quality of the fractures' network in EGS reservoir, which to a great extent determines the production potential of the EGS [5]. Some practical issues also lead to operation and maintenance costs, such as corrosion and scaling in wellbores and power plant components, and the loss of working fluid while circulating [6,7].

In this context, some researchers considered alternative systems to use deep geothermal energy, and particular attention was given

---

* Corresponding author.
E-mail address: fm_jiang2000@yahoo.com (F. Jiang).

https://doi.org/10.1016/j.energy.2018.08.055
0360-5442/

to the Downhole Heat Exchanger (DHE); DHE typically consists of a system of U-pipes or coaxial tubes suspended in the well, through which heat carrier fluid is pumped to extract the thermal energy from the well. Since the working fluid is circulated in a closed-loop system, the problems like fluid loss, corrosion and scaling are essentially avoided. DHEs have been widely used for the direct utilization of geothermal resources [8–11]. Recently, many studies presented analytical and numerical models to estimate the production potential of DHE geothermal systems used in abandoned oil or gas wells for mining HDR geothermal energy [12–18]. For instance, Kohl et al. [12] investigated the behavior of a heat exchanger installed at 2302 m subsurface in an abandoned borehole in Switzerland and the results indicated the produced thermal power increases from 40 kW to over 200 kW with a properly set fluid circulation rate. Nalla et al. [13] conducted a numerical study, which dealt with a vertical borehole drilled to a total depth of 5593 m; the results indicated that the system hardly supplies sufficient energy to generate 50 kW electrical power. Based on numerical results, Bu et al. [15] estimated the electrical power production of a DHE system and found the energy production from abandoned oil wells depends largely on the fluid flow rate and the geothermal gradient. Nevertheless, most of these studies considered only heat conduction between rock and well. Since the heat conduction flux from rock is primarily determined by thermal conductivity of the rock, heat exchange area and temperature difference between the average temperature of rock and working fluid [19], it is difficult to further improve the heat extraction performance of such a system, considering the limited number of parameters that can be altered.

Several conceptual designs about combining a permeable reservoir with a DHE system for HDR heat extraction were proposed [20–22]. Wang et al. [20] investigated a single-well DHE with connection to artificial fracture intervals, through which the working fluid was circulated to take advantage of the resulting thermosiphon effect. Feng et al. [21] proposed a coaxial DHE concept, in which a downhole pump was placed inside a horizontal wellbore to generate fluid convection for better heat transfer effect. Shi et al. [22] established a 3D unsteady state numerical model to study the coupling effect of ground water flow and the heat transfer of DHE system. These studies proved that convective flow and the buoyancy driven flow in permeable formation around wells can obviously increase the production capacity of DHE systems.

Another branch research direction regarding to DHEs is the application of heat pipe system. The heat pipe has the advantage of transferring heat very effectively from its high to the low temperature end relying on the working fluid phase transition. The heat pipe, compared with the U-tube or coaxial tube DHEs, has the advantage of not requiring external pumping power and it can enhance the heat transfer rate due to very high boiling and condensation heat transfer coefficients. Moreover, the heat pipe system is able to maintain a higher temperature difference between working fluid and reservoir, which will promote the fluid natural convection in reservoir and certainly lead to an increased heat extraction rate. Using heat pipe to harvest geothermal heat was reported by quite a few researchers [23–26]. Thermal performance of a conventional single-tube thermosyphon is generally limited by the counter-resistive interaction between the oppositely-flowing vapor and liquid. Vasil'Ev [23] proposed a variant heat pipe in 1990, in which an additional tube is added to separate the vapor and liquid flow, enabling its utilization in geothermal energy exploitation. Kusaba et al. [24] developed a 150 m-long heat pipe, in which the liquid feeding tube was equipped with showering nozzles to form a uniform liquid film over the large evaporator internal surface. More recently, Ebeling et al. [26] conducted simulation and experimental validation work of a 400 m-long geothermal heat pipe system, in which CO_2 was used as the working fluid of heat pipe. These studies indicate the heat pipe system has the potential for mining the earth-deep geothermal energy.

In this study, a novel design for mining hot dry rock geothermal energy is proposed, which is a combination of a fractured reservoir and a heat pipe system. The basic configuration is a heat pipe system installed in a single-well with the purpose of extracting geothermal energy. In addition, a fractured reservoir is built around the main endothermic region of the well, which is permeable and saturated with a second working fluid. A heat pipe, instead of a pump-assisted flow through a U-tube or coaxial tube, is used to transfer geothermal heat to the up-ground. During the heat extraction process, the temperature difference between the evaporator of heat pipe and rock can induce a natural flow in the reservoir, which will lead to an increased heat flux between the wellbore and reservoir. Thus, the proposed system can have a higher heat production as compared to the conduction-only DHE system, while it shares all the advantages of the closed-loop DHEs mentioned in the previous paragraphs.

The objective of the present work is to assess the production potential for mining hot dry rock geothermal energy by this combined Reservoir and Heat Pipe System (RHPS). Detailed sensitivity analyses are conducted taking into consideration a wide range of possible configurations such as well geometry and depth, working fluid, and operation conditions, with the aim of understanding how operation and design variables affect the heat extraction performance of the system and providing guidance towards improved the design of RHPS.

2. The combined reservoir and heat pipe system

The RHPS we propose for mining hot dry rock geothermal energy combines features of the heat pipe and the fractured reservoir, as depicted in Fig. 1. A heat pipe, instead of a pump-assisted flow through a U-tube or coaxial tube, is placed into a vertical well to extract geothermal energy. An annulus flow channel exists between the wellbore casing and the heat pipe outer shell. In addition, a reservoir is built around the main endothermic region of the well, which is permeable and saturated with a second working fluid.

The RHPS requires a permeable reservoir saturated by the working fluid in order that natural convective flow is induced by the thermosyphon effect. The wellbore casing in the reservoir region allows the reservoir working fluid flowing across the heat pipe evaporator surface, as depicted in Fig. 1. During heat extraction, the temperature difference between well and rock induces a natural convective flow in the reservoir, which will lead to an increased heat flux at the heat pipe evaporator outer surface. The working fluid in the reservoir and that in the heat pipe are segregated. The proposed system uses CO_2 and water (or other suitable fluid) as the working fluid in the reservoir and in the heat pipe, respectively; CO_2 is an attractive geothermal working fluid because its specific thermodynamic and fluid dynamics properties suggest that it can transfer geothermal heat more efficiently and its large thermal expansion coefficient contributes significantly to the buoyancy force. Pruess [27] quantitatively evaluated the heat extraction of an EGS plant at Soultz-sous-Forêts using CO_2 as the working fluid. The simulation results indicate that the heat extraction rate with CO_2 is approximately 50% higher than that for water. It is also noted that the use of CO_2 as the working fluid in the reservoir would have the ancillary benefit of providing geologic storage for the CO_2. Randolph et al. [28] demonstrated that combining geothermal energy extraction with CO_2 sequestration vastly improves the economic feasibility of the CO_2 capture and storage.

A heat pipe, instead of a pump-assisted flow through a U-tube or