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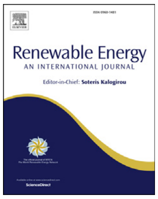

Heat extraction of novel underground well pattern systems for geothermal energy exploitation

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ABSTRACT

The current Enhanced Geothermal Systems (EGS) with a fractured reservoir undergoes several practical issues, such as scaling in the wellbore, the mass flow loss into the reservoir, and the challenge in designing the placement of production wells. In this paper, novel underground well pattern systems were proposed for geothermal energy exploitation. A numerical model of two kinds well pattern systems (multi-horizontal-wells system and annular-wells system) were setup taking into account the heat exchange with the surrounding formation. The numerical model was validated by the logging data from Ordos CO_2 geological storage demonstration project, China. A comparison between the well pattern system and a fractured reservoir was conducted based on European EGS site at Groβ Schonebekc, Germany. Results showed that when the horizontal well length of well pattern system was about 10 times to the fractured reservoir, the production wellhead temperature and pressure of eight horizontal wells system with CO_2 were respectively 38.9 °C higher and 10.9 MPa higher than that of the fractured reservoir system with CO_2 after 20 years at a flow rate of 20 kg/s, an injection temperature of 20 °C and an injection pressure of 10 MPa, showing a significant application potential of the well pattern system.

1. Introduction

Under the stresses of greenhouse gas control and environmental conservation, the whole world has been increasingly attaching importance to the renewable energy. Geothermal energy, among all the types of the renewable energy, has huge potentials spread all over the earth and own advantages on the consistently stability regardless of the external weather and time. IEA (International Energy Agency) predicted that, geothermal electricity generation could get to 1400 TWh per year by 2050, contributing around 3.5% of the forecast global electricity consumption in the world for that year [1].

Geothermal fields could be utilized for heat direct use or for electrical power generation [2]. Geothermal power plants, based on high temperature hydrothermal reservoirs, are operating in at least 24 countries in the world, having a power capacity of nearly 11.0 GWe by 2010 [3], however, restricted to a few areas for the essential demands for ground water and high permeability. Enhanced Geothermal Systems (EGS), with a reservoir of low permeability, low fluid content and low hydraulic connectivity, but existing everywhere, has been proposed [2]. Up to now, some EGS demonstration projects have been operating in the world, e.g., the Fenton Hill and Desert peak projects in the United States, Rosemanowes project in UK, Soultz-sous-Forêts project in France, Hijiori project in Japan, Cooper basin project in Australia, Deep Heat Mining (DHM) projects in Switzerland, and Gross Schoenebeck project in Germany [4,5]. China also increases emphasis on the development of geothermal energy since the government has announced a target to reduce the greenhouse gas emissions at around 2030 and use non-fossil fuels for 15% of its energy structure by 2020 [4].

In EGS projects, the working fluid is pumped into reservoir through injection wells to extract the geothermal energy, enters energy conversion system on the ground or the heat use facilities from the production wells for generating electricity or heat use, and then recirculated underground. Initially the reservoir is hydraulic fractured by pressurized water to improve the permeability and to create hydraulic conductivity between the injection wells and the productions wells. Investigations on heat extraction and power

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generation of EGS have been conducted by many researchers. Li and Lior [6] analyzed and compared leading geothermal power plant configurations with a geofluid temperature from 200 to 800 °C, and also analyzed the embodied energy of EGS surface power plants. Li and Lior [7] also analyzed fracturing and thermal performance of fractured reservoirs in EGS from a depth of 5 km–10 km using an improved model for flow and heat transfer. Effects of the geofluid flow direction choice, distance between fractures, fracture width, permeability, radius, and number of fractures, on reservoir heat drawdown time were obtained. Chen and Jiang [8] numerically simulated the heat extraction process of EGS with various well layouts, including the standard doublet well layout, two triplet well layouts, and a quintuplet well layout assuming the created heat reservoir could be treated as a homogeneous porous medium. Their simulation results enabled a detailed analysis on the influences of well layout on EGS heat extraction performance. Ekneligoda and Min [9] presented a nomogram solution for the evaluation of the production temperature that incorporated the mass flow rate, fracture width, fracture length, number of conductive fractures, host rock temperature, and the production time of EGS by using both an analytical and numerical model. Bujakowski et al. [10] conducted numerical modeling using TOUGH2 code to evaluate the energy performance of the prospective EGS plant operating in the Lower Triassic sedimentary formations of the Polish Lowland. Results indicated that the energy performance of the EGS plant was strongly dependent on the volume and permeability of the artificially fractured zone. Zhang et al. [11] conducted comparison of system thermodynamic performance of CO_2-EGS and water-EGS systems.

However, the Enhanced Geothermal Systems with a fractured reservoir undergoes several practical issues, such as the huge demand for water, large pressure drop through the fractured reservoir, corrosion and scaling in the wellbores due to the direct contact of the working fluid with the reservoir rock surface, the mass flow loss into the reservoir and the challenge of choosing production well drilling location due to the difficulty in controlling the fracture channels. For instance, in Rosemanowes project in UK, when the injection rate was 5 l/s, the return from the production well was 4 l/s; when 24 l/s was injected, only 15 l/s was produced [5]. In Hijiori project, the production wells had to be cleaned-out due to scaling problems and the flow rate loss was as high as 45% during long-term test from 2000 to 2002. The test was finally stopped due to the drop in production temperature which was larger than the numerically predicted temperature drop [5]. Therefore, an ideal geothermal exploitation method should have a comprehensive advantage on generating efficiency, pressure drop, environmental impact, cost, and flow rate loss. Currently, the field-scale heat extraction efficiency and generating efficiency can merely be obtained through simulation tools. However, the heat transfer models in the complex subsurface structures were still insufficient [4], and no EGS reservoir has been operated for a sufficient period of time to provide the required data to validate a simulation model [2]. This brings more uncertainty on EGS with fractured reservoir when the fractured channels lead to uncertain flow and reservoir behavior under long-term energy extraction.

In this context, some researchers proposed new subsurface heat exchangers to improve the comprehensive performance of the heat extraction system. Alimonti and Soldo [12] analyzed the possibility to implement a wellbore heat exchanger on one of the largest European oil fields: the Villafortuna Trecate oilfield and demonstrated the importance to consider the change of fluid properties inside the exchanger. Galgaro et al. [13] analyzed the feasibility and sustainability of borehole heat exchangers in shallow geothermal areas which circulated a working fluid in a closed-loop of pipes installed vertically in a deep well and released the heat to buildings. It is found that an array of 4 heat-exchangers 240 m deep provided enough thermal energy to the building. Yekoladio et al. [14] designed and optimized a downhole coaxial heat exchanger employed in an Enhanced Geothermal Systems where cold water was injected from the annulus and produced from the inner tube, to maximize the cycle power output. Dehkordi et al. [15] found that in downhole heat exchangers, proximity of the pipes to the borehole wall was more important than the pipe separation in reducing the total borehole resistance. Hence, they proposed and numerically modeled a tight borehole design with little spacing between the down-hole pipes and the borehole wall. Finsterle et al. [16] used numerical simulations to explore the potential of injecting the fluid from micro-hole arrays rather than a few conventionally drilled wells to increase the heat extraction efficiency and sustainability of EGS. Results showed that micro-hole arrays provided pathway to a larger reservoir thus increasing the heat recovery factor; more importantly, the risk of preferential flow and early thermal breakthrough was reduced in microhole-array-based EGS. Jeanloz and Stone [17] discussed a closed wellbore pattern system where the working fluid flowed through wholly drilled heat exchangers. It was found from a simple heat transfer calculation that for a reservoir with the initial temperature of 250 °C, assuming water production temperature to be 150 °C (where the inlet temperature was 50 °C) after 10 years' operation, the heat exchanger should have a total length of about 2.5 km with the diameter of 1.3×10^{-2} m in order to still produce 1 MW thermal power after 10 years. Furthermore, after 40 years' operation, the thermal power produced would only have decreased by 10% to 0.9 MW. The underground closed-cycle heat exchanger system, as one of the fifteen geothermal power generation projects supported by the German government, was in the charge of Prof. Wolff from Berlin Institute of Technology [18]. The underground system included two vertical wells with the depth of 3–5 km per well and one horizontal well in which the working fluid was circulated and heated by the reservoir. On the ground, Organic-Rankine-Cycle (ORC) was used for electricity generation. Wolff stated that the underground closed-cycle heat exchange system, compared to EGS with fractured reservoirs, had advantages on the non-decreasing flow rate of the working fluid, little contamination on the reservoir, low cost of system maintenance, and long lifetime. With one horizontal well, the reservoir near the pipe center was cooled dramatically; hence, Wolff suggested to consider multi-horizontal-wells system [18]. However, based on the concept of the underground closed-cycle heat exchanger system, very few quantitative system analysis and simulation about the heat extraction performance especially with the multi horizontal wells were conducted.

In this paper, novel underground well pattern systems, replacing fracturing technology with horizontal wells technology, were proposed for geothermal energy exploitation. Different from the already proposed underground closed-cycle heat exchange system [17,18], the proposed underground well pattern systems in this paper contained multiple horizontal wells with the distance between each wells carefully designed to avoid the thermal breakthrough, or contained annular wells where the injection and production wellhead were close to each other to reduce the pressure loss in the transport pipelines on the ground. The proposed well pattern systems had dramatic advantages in solving scaling problem due to the flow inside of the wellbores, precisely controlling the flow direction and mass flow rate without loss, as well as decreasing the pressure drop from the injection well to the production well which increased the thermal efficiency. With greenhouse gas control gaining increasing attention, CO_2 can be sequestered in deep or shallow aquifers [19–21], be used to enhance CH_4 recovery [22] and to extract geothermal energy as the working fluid in EGS [23]. For EGS with CO_2 as the working fluid,