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Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells

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HIGHLIGHTS

- A novel multilateral-well EGS is proposed.
- A 3D fluid flow and heat transfer model for multilateral-well EGS is presented.
- Flow and temperature fields in reservoir of multilateral-well EGS are discussed.
- Performances of double-well EGS and multilateral-well EGS are compared.
- Performances of various well arrangements for multilateral-well EGS are discussed.

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ABSTRACT

A novel enhanced geothermal system with multilateral wells is proposed to extract heat from hot dry rock in this study. For this EGS, one main wellbore is drilled to hot dry rock. Several injection and production multilateral wells are side-tracked from the main wellbore in upper and lower formation, respectively. An insulated tubing is installed in the main wellbore. The working fluid is injected from the annulus and injection wells and then extracts heat from the hot dry rock reservoir. Subsequently, the working fluid is produced from production wells and returns to surface through the insulated tubing. In this study, an unsteady-state fluid flow and heat transfer 3D model is presented to investigate the heat extraction performance of the multilateral-well EGS. The model is verified by a known analytical solution. The temperature and velocity fields of the multilateral-well EGS are analyzed and heat extraction performances of four various well types are compared. The results indicate that the output thermal power, production temperature, heat extraction ratio and accumulative thermal energy of the multilateral-well EGS are higher than those of conventional double vertical wells EGS. This study provides a better alternative for EGS to obtain greater heat extraction performance.

1. Introduction

Geothermal energy is one of the promising and clean renewable energy resource alternatives to fossil fuels such as coal, oil, and natural gas. Geothermal energy is stable and does not rely on weather conditions; hence, it is superior to wind power, solar power, and tidal power. Therefore, geothermal energy has been widely used for electricity generation by many countries, including Iceland, Kenya, Indonesia, Turkey, and the United States. [1].

The heat stored in hot dry rock (HDR), which is distributed within subsurface of 3–10 km depths, is one common form of geothermal energy. Compared with the hydrothermal system, HDR heat is more abundant (more than 1.4×10^{25} J in the United States and approximately 2.52×10^{25} J in China) [2,3] and the temperature is higher (normally up to 150–650 °C) [2]. Therefore, HDR has enormous potential to generate electricity. A few decades ago, the enhanced geothermal system (EGS) was proposed to exploit heat from HDR and many field tests of EGS have been carried out in the United States, France, and Australia, such as the Fenton Hill EGS, Soultz EGS, Desert Peak EGS, and Cooper Basin EGS [4]. In the conventional EGS, two vertical or directional wells are drilled as injection and production wells, and an artificial heat reservoir is created by the hydraulic fracturing process. In this study, we propose a novel EGS with multilateral wells. Its schematic is illustrated in Fig. 1. For this EGS, one main wellbore is drilled to HDR. Subsequently, a radial jet drilling (RJD) technology [5,6] or microhole coiled-tubing (CT) drilling technology

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Nomenclature

$c_{p,f}$	working fluid heat capacity, J/(kg·K)
$c_{p,s}$	heat capacity of the solid part in the reservoir, J/(kg·K)
EGS	enhanced geothermal system
d	day
d_f	fracture aperture, m
erfc	complementary error function
g	gravitational acceleration, m/s^2
HDR	hot dry rock
k	reservoir permeability, m^2
k_f	fracture permeability, m^2
L	total length of multilateral production wells, m
P	output thermal power, W
PDE	partial differential equations
p	pressure, Pa
q	volumetric flow rate, m^3/s
SRV	stimulated reservoir volume
t	time, s
T	temperature in the porous media, K
T_f	temperature in the fracture, K
T_i	initial temperature of the porous media, K
T_{in}	injection temperature, K
T_{out}	average production temperature, K
$T(t)$	temperature at time instant *t*, K
U	unit step function
u	Darcy velocity in the porous media, m/s
u_f	Darcy velocity in the fracture, m/s
u_{in}	injection velocity, m/s
V_s	volume of the SRV, m^3
V_R	volume of the enclosing rock, m^3

Greek symbols

ρ_f	working fluid density, kg/m^3
ρ_s	density of the solid part in the reservoir, kg/m^3
μ_f	working fluid viscosity, Pa·s
λ_f	working fluid heat conductivity, W/(m·K)
λ_s	heat conductivity of the solid part in the reservoir, W/(m·K)
φ	reservoir porosity
φ_f	fracture porosity
η	heat extraction ratio
γ	accumulative extracted thermal energy, J
α	compensation ratio

[7] is employed to side-track several multilateral wells from the main wellbore at the upper and lower formation. The length of the multilateral wells could be extended to 100 m by RJD and 2000 m by microhole CT drilling, while the maximum diameter ranges from 0.05 to 0.08 m [7,8]. More detailed descriptions about multilateral well drilling technologies can be found in the Refs. [5–8]. Next, hydraulic fracturing is conducted to open and extend the natural fractures and produce primary artificial fractures between the upper injection and lower production wells. Fracturing could promote HDR cracking and fracture network formation to create a stimulated reservoir volume (SRV) in HDR. Finally, an insulated tubing is installed in the main wellbore and the annulus between the tubing and wellbore is sealed by a packer. The working fluid is injected from the annulus and injection wells into the SRV, where it extracts heat from HDR. Afterwards, the working fluid is produced from the production wells and returns to the surface for electricity generation through the insulated tubing. It is worth noting that the positions of the injection and production multilateral wells can be reversed, i.e. the production wells are located in the upper formation while the injection wells are in the lower formation, and the working fluid is injected from the insulated tubing and produced from the annulus.

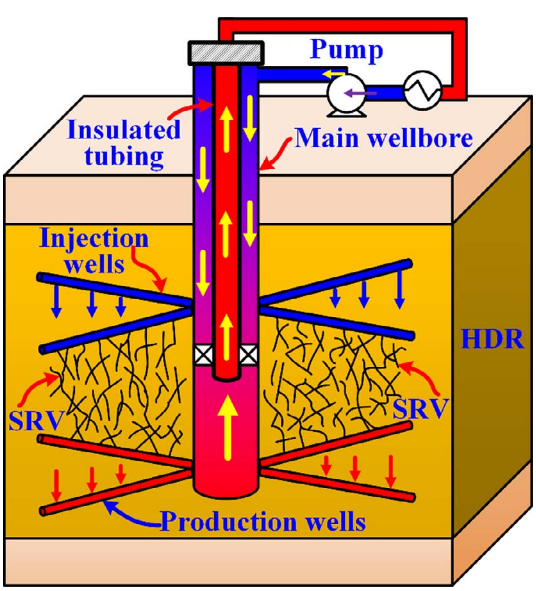

Fig. 1. Schematic of heat extraction for multilateral-well EGS.

With multilateral-well EGS, only one main wellbore is required to be drilled to accomplish injection and production simultaneously. Therefore, compared with the conventional double-well EGS, it could significantly reduce the cost of geothermal development, because the drilling cost of one 4500–5000 m wellbore in EGS is approximately 13–15 million dollars, which accounts for more than 50% of the total project cost [9]. Moreover, multilateral wells are drilled to enhance the connectivity of the wellbore to HDR and the fractures, thereby improving the wellbore productivity and injectivity. Currently, there are many field applications of multilateral wells in the petroleum industry [10,11] and there is one example for an application in the geothermal energy development. In 2008, 12 multilateral wells with a length of approximately 40 m were side-tracked using the radial jetting technology from an injection well at Klaipėda geothermal field to obtain an improvement in injectivity of approximately 14% [8]. Hence, the multilateral-well EGS has potential for achieving high heat extraction performance in HDR development.

The simulation methods, including numerical and analytical model, have been proved to be useful and effective tools to investigate the heat extraction process in the geothermal system [12,13]. For borehole heat exchange geothermal systems, Shi et al. [14] established a numerical model to study the heat production capacity of the reservoir. The effects of the key factors, such as subsurface water flow, reservoir properties, and heat exchanger configuration, on the heat extraction performances of geothermal systems were studied by numerical methods [15–19]. Furthermore, analytical models, such as the helical-line-source model [20], ring-coil-source model [21], and cylindrical heat source mode [22], etc., were also widely utilized for the optimization and design of heat exchangers. For EGS, the complex process involves heat transfer, fluid flow, stress changes, rock deformation, and geochemical reactions, which are combined as a thermo-hydro-mechanical-chemical (THMC) process [23]. The fracture system could be represented by two methods, namely the discrete fracture network model and the equivalent continuous porous media model [24–26]. In addition, the heat transfer between the solid and fluid in the EGS reservoir is described by two models, known as local thermal equilibrium and local thermal non-