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Research Paper

Parametric study of an enhanced geothermal system based on thermo-hydro-mechanical modeling of a prospective site in Songliao Basin

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HIGHLIGHTS

- EGS reservoir simulation with thermo-hydro-mechanical coupling was carried out.
- Hydraulic conductivity is enhanced due to the thermal stress during production.
- Permeability and porosity play major role in terms of the productivity.
- For a vertical fracture, increasing fracture thickness improves the productivity.
- For vertical wells, production wells should be deeper than injection well.

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ABSTRACT

The promising technology of Enhanced Geothermal System (EGS) using the vast extent of geothermal energy resources proves to be feasible according to research conducted over the past few decades, whereas there is still a lack of thorough understanding of the underground process. Thermo-hydro-mechanical modeling of a conceptual reservoir based on the geological setting of a target area in Songliao Basin was carried out. The effects of the geological background and the parameters determined during the stimulation and production processes were investigated regarding the output of the reservoir. The results demonstrated that properties that are able to strength the heat convection in the reservoir is able to evaluate the power output significantly, and wellbore arrangement that takes advantage of the buoyancy flow is also a valuable way to increase the production.

1. Introduction

As one of the renewable energy resources, geothermal energy is abundant but underdeveloped [1]. The fact remains that geothermal fields of sufficient quality to produce economic electricity are rare, and thus the tapping of geothermal energy is limited to a handful of locations [2].

The promising untraditional means of Enhanced Geothermal System (EGS) makes these ubiquitous resources accessible. Normally, hydraulic stimulation is applied to increase the permeability and expand the heat transfer area of the fractured reservoir, and water is injected to be heated and pumped out. In a typical EGS project, we first stimulate a large rock volume, drill into the stimulated region to establish a connected reservoir, circulate fluid with acceptable pressure losses at near commercial rates, and generate power at the ground surface using the produced thermal energy. The total costs of a EGS project was subdivided into five categories: drilling cost, production cost, costs for feed pumps and surface installations, stimulations cost, and other operational costs [3]. Hofmann, etc. estimated that for an EGS project with 3 wells of 5 km, the cost of drilling makes up 51% of the total cost, and pumping cost for one injection well and two production wells is approximated to be 42% [3]. Therefore, costs of EGS projects can vary significantly depending on the production scheme and the effectiveness of stimulation. For a specific EGS site, the stimulation scheme and drilling plan should be optimized to achieve better hydraulic and thermal performances at the production stage [4,5].

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Nomenclature

c_r	rock specific heat, J/(kg °C)
$\overline{F}$	body force per area, Pa
E	Young's modulus, Pa
$\mathbf{g}$	gravitational acceleration, m/s^2
G	shear modulus, Pa
H	depth of the well, m
h	specific enthalpy of injection, J/kg
k	permeability, m^2
K	bulk modulus, Pa
$\dot{m}$	mass flow rate, kg/s
P	pore pressure, Pa
q	source term, kg/m^3 or J/m^3
T	temperature, °C
T_{ref}	reference temperature, °C
$\mathbf{u}$	velocity vector, m/s
u_w	internal energy, J/kg
W_h	heat output, W
W_p	pump consumption, W
α	Biot's coefficient, dimensionless
β	linear thermal expansion coefficient, °C^{-1}
ϕ	porosity, dimensionless
ϕ_0	initial porosity, dimensionless
η_h	energy efficiency, dimensionless
η_P	pump efficiency, dimensionless
λ	Lame's constant, Pa
λ_r	rock thermal conductivity, W/(m K)
ε_v	volumetric strain, dimensionless
$\overline{u}$	displacement vector, m
v	Poisson's ratio of rock, dimensionless
σ_m	mean normal stress, Pa
ρ	density, kg/m^3
μ	viscosity, Pa s

Subscripts

inj	injection well
pro	production well
r	rock
w	water
m	mass
h	heat

Over three decades of research and development of EGS reservoirs in several countries, certain experiences were gained, and a number of problems were revealed [6]. The first attempt to make a full-scale EGS reservoir in the Fenton Hill demonstrated the feasibility of hydraulic conductivity enhancement through stimulation. However, the marked water loss rate indicated that water pressure should be controlled to avoid the reservoir growing and to minimize water losses. The pilot EGS power plant in Soultz successfully created an artificially stimulated reservoir of commercial size although with production rates still below required levels for an economical power plant. One of the production wells, GPK2, was stimulated in the open-hole section from 3211 to 3876 m, forming a stimulated volume of about 0.24 km^3 [7]. Additionally, the injection well GPK3 was stimulated to extend the existing reservoir of GPK2 by an overlapping volume of enhanced permeability. Another injection well GPK4, which was separated from the two production wells by about 650 m and 600 m, was stimulated [7]. In the cooper basin in Australia, stimulation in the well Habanero-I was carried out at depths between 4136 m and 3994 m, and the fractured volume was extended to cover a horizontal pancake-shaped area of 4 km^2 in the year 2005 [6]. The Ogachi project was also considered as an EGS project as the temperatures were high and the productivity was low. Two fractures were stimulated while each of them was only created in 10 m of open hole in the well bottom. After stimulation in the production well, the recovery rate was improved from 3% to 25%, whereas still being small [8]. One of the lessons learned at Ogachi is that although the permeability after fracturing was found to be 10^{-4}–10^{-5} cm/s, a relatively high value, the mass flow rate at the producer was still small as the total fractured reservoir volume was only about 250 m^3, suggesting that efforts to connect the two wells should be enhanced in addition to enhancement of the reservoir permeability [8]. Another EGS project in Japan, the Hijiori project, has one injector and two producers. It was demonstrated that the reservoir grew and the permeability was elevated even more during circulation tests than during the stimulation process, emphasizing the mechanical effects as water flow in the reservoir [9]. Generally, in these EGS projects, two or three wells were drilled to a depth of 3000–4000 m for heat mining. Most of the recovery rates remain low, which were influenced both by the connectivity of the reservoir, namely permeability, and the scale of the reservoir. Sufficient reservoir volume and heat transfer area are crucial to the hydraulic and thermal performances [4,5], but water loss and expense would be significant simultaneously. Besides, the pressure gradient should be controlled to avoid reservoir expansion and permeability enhancement that will induce water loss. Accordingly, reservoir design and well arrangement should be optimized to achieve better performances based on an understanding of the production process.

The dynamic production process was numerically investigated based on thermo-hydro-mechanical coupling of the reservoir in our study. A target area in north of Songliao Basin was simulated. Then parametric study was implemented to identify the factors that influence the production process, and suggestions for optimization of the production were derived.

2. Numerical model with thermo-hydro-mechanical coupling

2.1. Model description

Fluid and heat flows are coupled with geomechanical effects for field-scale reservoir modeling. Geomechanics is fully coupled and developed from the linear elastic theory, and is formulated with the mean normal stress as well as pore pressure and thermal stress. The fluid flow and heat transfer portion is based on the general-purpose numerical simulator TOUGH2 [10,11]. Fluid flow is described with a multiphase extension of Darcy's law, and heat flow is governed by conduction and convection as shown by Eqs. (1) and (2).

$$\frac{d}{dt}(\phi\rho_w\mathbf{u}) = -k\frac{\rho_w}{\mu_w}(\nabla P - \rho_w\mathbf{g}) + q_m \tag{1}$$

$$\frac{d}{dt}(\phi\rho_w u_w + (1-\phi)\rho_r C_r T) = -\lambda_r\nabla T + \rho_w h_w\mathbf{u} + q_h \tag{2}$$

Assuming that boundaries of each block element can move as an elastic material, the Hooke's law for thermo-poro-elastic medium is given by