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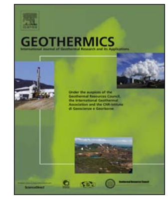

Performance of an open-loop well-doublet scheme located in a deep aquitard–aquifer system: Insights from a synthetic coupled heat and flow model

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ABSTRACT

Understanding hydrothermal processes during production is critical to optimize geothermal reservoir operation and reduce the risk of its failure. The influence of the subsurface physical parameters, the design of the wells, and their operational settings on a high-enthalpy liquid-dominated geothermal operation has been investigated. For this purpose, a numerical model was developed, accounting for the flow, mass and heat transport in a single-phase aquitard–aquifer system, in the vicinity of a vertical 4-km well-doublet scheme. The sensitivity analysis varies the thermal power from 34.0 MW_t to 58.1 MW_t and the productivity index altered within the range 0–4.9 $\times 10^2 \, l \, s^{-1} \, bar^{-1}$. The parameters affecting both the hydraulic and thermal performances are (1) the reservoir permeability, (2) the injection temperature, (3) the production/injection rates, (4) the aquifer thermal conductivity, and (5) the length of the openhole section. These parameters provide a general control of the project and should be carefully estimated and designed. The predominant role of the aquifer parameters over the aquitard parameters is clearly demonstrated in this specific study. However, ignoring the caprock and bedrock in the model simulations would result in strongly and negatively biased estimates of the reservoir temperatures.

1. Introduction

In the past decades, geothermal energy has provided an option for base load electricity even if its use appears to be often marginal in national energy systems. In the pursuit of sustainable energy sources, the interest in geothermal resources has increased in recent years (Lund et al., 2011). Initially limited to regions with high geothermal gradients, technology is now available for a wide range of geothermal conditions: from medium-low to high enthalpy types, as pointed out by Stefánsson (2005).

A common form of geothermal extraction involves extracting hot water from an aquifer from a production well, and re-injecting cooled water in a second injection well within the same aquifer. This system is a typical well-doublet scheme. Reinjection of cooled water within the reservoir started as a method of waste water disposal (Stefansson, 1997; Sanyal et al., 1995), but now has become one of the key factors in the success or failure of the field (Diaz et al., 2016). Reinjection provides pressure support, reducing drawdown and the potential for subsidence (Kaya et al., 2011). Also, this process increases the longevity of geothermal resources and the amount of energy that can be recovered (Gringarten and Sauty, 1975). As the operation takes place, a cooled water zone will spread over time from the injection well, eventually reaching the production well. After thermal breakthrough occurs, the outlet temperature is no longer constant, which may have significant consequences for the overall sustainability of the project. Therefore, a careful design of the production-injection system is required for an optimal geothermal development of the field, as well as to prevent an early thermal breakthrough at the production well (Diaz et al., 2016). The cyclic mode version of doublet operation corresponds to Aquifer Thermal Energy Storage (ATES), where the flow can be reversed so as to store heated and cooled water. Early field experiments involving ATES systems can be found in Molz et al. (1981, 1979, 1978), while successful applications of seasonal storage for the purpose of cooling and heating buildings are described in Paksoy et al. (2004, 2000). The success of open-loop operation requires an accurate knowledge of the geological system and the geothermal plant. This can explain why this methodology is well developed for shallow formations (Kazmann and Whitehead, 1980; Banks, 2009) but remains limited for deeper formations located in sedimentary basins (3–7 km) involving higher temperatures (> 150 °C).

Moreover, at depth, one of the challenges is the low permeability of the host rock. The increasing pressure often leads to a decreasing

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porosity, related to the cementation of poral voids. Associated with open-loop exploitation, the forced circulation of fluid within the aquifer can increase the local productivity. This kind of geothermal exploitation, associated with an increase of production over its natural state, is within the scope of the broadest definition of Enhanced Geothermal Systems (EGS) (Tester et al., 2006; Williams et al., 2011). Most EGS systems are developed in dry rocks, such as magmatic or volcanic formations, with minor convection processes associated with natural flows. Convection is limited to aquifer formations where natural groundwater flow processes occur under natural conditions, such as deep sedimentary aquifers.

Thus, liquid-dominated high-enthalpy systems located in deep sedimentary basins with normal geothermal gradient constitute the resource of interest. Despite their potential, exploitation of deep hydrothermal systems remains limited. The high cost of installation of deep boreholes is the key to this limitation, and the risk of failure is non-negligible. Geological uncertainties are the first issue, as the facies and the properties of the rocks are of major importance. Moreover, the hydrogeological processes are more complex, because both conductive and convective processes can occur (Magri, 2005). Numerical modeling is helpful to understand the thermal transport processes at the basin scale (Blöcher et al., 2010; Magri et al., 2009b; Noack et al., 2013; Oldenburg and Pruess, 1998). At the local scale, numerical modeling provides details of open-loop exploitation (Banks, 2009), but has often been limited to shallow formations (Abesser, 2010; Lee, 2014; Russo and Civita, 2009; Handel et al., 2013; Russo and Taddia, 2010). It is essential for an open loop system to optimize the design of wells to meet the heating or cooling demands and economic considerations. Numerical modeling provides an efficient tool for testing alternative scenarios of exploitation and well configuration to evaluate development risks induced by limited geological data at great depths.

In the present paper, a synthetic deep confined aquifer containing single-phase liquid water is considered, to study the characteristics and critical parameters associated with a deep doublet production system. Design parameters such as the hydraulic performance of the doublet, production rate, injection temperature, and screen length are evaluated. Besides, the influence of the thermal and hydrodynamical parameters of the sedimentary reservoir is studied.

2. Numerical modeling of the deep geothermal doublet

The model of a deep geothermal doublet is developed using FEFLOW® code, which is a three-dimensional finite-element groundwater flow, mass and heat transport modeling software developed by DHI-WASY GmbH (DHI, 2014). From this point on, all the variables whose units are not explicitly shown are dimensionless quantities.

2.1. Governing equations

Thermohaline processes in a saturated porous medium are strongly coupled with the mass concentration, the pressure, and the temperature, as they control the fluid density and viscosity. The following set of differential equations describes the balances of the fluid mass, linear momentum, the solute mass, and heat (e.g., Bear, 1991; Kolditz et al., 1998; Nield and Bejan, 1999).

In three dimensions (3D), and in two (2D), the mass conservation of a fluid in a fully saturated porous medium is expressed by Eq. (1) (i, $j = 1, 2, 3$)[1]:

$$\left[S_s\frac{\partial h}{\partial t} + \frac{\partial q_i}{\partial x_i} = Q_p\right] \equiv \left[S_s\frac{\partial h}{\partial t} + \nabla q = Q_p\right] \tag{1}$$

[1] Note that for all vectorial and tensorial quantities having repeated indices, Einstein's summation convention will be generally employed throughout this paper, e.g., $(\partial q_i/\partial x_i) \equiv (\partial q_1/\partial x_1) + (\partial q_2/\partial x_2) + (\partial q_3/\partial x_3)$ in the three-dimensional case.

where S_s (m^{-1}) is the specific storage coefficient, h (m) is the hydraulic head, Q_p (s^{-1}) is the source/sink function of the fluid, and q_i (m s^{-1}) is the Darcy velocity vector of the fluid defined by

$$q_i = -K_{ij} f_\mu \left(\frac{\partial h}{\partial x_j} + \frac{\rho_f - \rho_{f,0}}{\rho_{f,0}} e_j\right) \tag{2}$$

where K_{ij} (m s^{-1}) is the hydraulic conductivity tensor expressed in the constitutive fluid viscosity relation function f_μ and fluid density ρ_f (kg m^{-3}), e_j is the gravitational unit vector such that $g_j = -ge_j$, where g_j (m s^{-2}) is the gravity vector and g (m s^{-2}) denotes the acceleration due to gravity.

The complete heat equation (convective and conductive parts) is Eq. (3) (Diersch et al., 2011):

$$\frac{\partial}{\partial t}\rho_a c_a T + \frac{\partial}{\partial x_i}(\rho_f c_f q_i T) - \frac{\partial}{\partial x_i}\left(\Lambda_{ij}\frac{\partial T}{\partial x_j}\right) = Q_t \tag{3}$$

where $\rho_a c_a$, respectively, $\rho_f c_f$ (J m^3 K^{-1}), are the volumetric heat capacity of the bulk medium and the fluid, T (K) the temperature of the medium, and Q_t (kg m^{-1} s^{-3}) the source/sink function of heat. The tensor of hydrodynamic thermodispersion Λ_{ij} (kg m s^{-3} K^{-1}), detailed in Eq. (4), is expressed in terms of its conductive and dispersive parts:

$$\Lambda_{ij} = \Lambda_{ij}^{cond} + \Lambda_{ij}^{disp} = \lambda_a\delta_{ij} + \rho_f c_f\left[\alpha_T V_q \delta_{ij} + (\alpha_L - \alpha_T)\frac{q_i q_j}{V_q}\right] \tag{4}$$

where λ_a (J m^{-1} s^{-1} K^{-1}) is the thermal conductivity of the bulk reservoir, δ_{ij} is the Kronecker tensor, V_q (m s^{-1}) is the absolute Darcy fluid flux, and α_L (m), respectively, α_T (m), are the longitudinal and transverse dispersivity (with respect to the direction of groundwater flow).

The volumetric heat capacity $\rho_a c_a$ (Eq. (3)) and the thermal conductivity λ_a of the bulk reservoir (Eq (4)) are derived from the weighted arithmetic means of the fluid f, respectively, solid matrix s, thermal properties with respect to the total porosity ω by Eqs. (5) and (6), (Somerton, 1992):

$$\rho_a c_a = \omega\rho_f c_f + (1-\omega)\rho_s c_s \tag{5}$$

$$\lambda_a = \omega\lambda_f + (1-\omega)\lambda_s \tag{6}$$

In a deep geothermal application, the physical parameters of the fluid are highly dependent on environmental subsurface conditions, such as the mass concentration of the chemical component C (kg m^{-3}) as total dissolved components (TDS), the pressure p (kg m^{-1} s^{-2}), and the temperature T. To solve this system of equations, one needs constitutive relations for the density ρ_f and the viscosity μ_f (kg m^{-1} s^{-1}) of the fluid, notably in the definition of the hydraulic conductivity tensor K_{ij} according to (7):

$$K_{ij} = \frac{k_{ij}\rho_f(C, p, T)g}{\mu_f(C, T)} \tag{7}$$

where k_{ij} (m^2) is the permeability tensor of the solid matrix.

Eq. (8) gives the linear approximation of the equation of state for the fluid density as a function of pressure, temperature, and concentration references, respectively p_0, T_0, C_0, as well as the maximum concentration C_m:

$$\rho_f(C, p, T) = \rho_{f,0}\left(1 + \bar{\gamma}(p - p_0) - \bar{\beta}(T - T_0) + \frac{\bar{\xi}}{(C_m - C_0)}(C - C_0)\right) \tag{8}$$

where the fluid compressibility $\bar{\gamma} = \bar{\gamma}(p, T)$ (kg^{-1} m s^2), thermal expansion coefficient $\bar{\beta} = \bar{\beta}(T, p)$ (K^{-1}), and density ratio difference $\bar{\xi}(T, p)$ are derived for reproducing the fluid density of aqueous sodium chloride (brine) solution in the single liquid phase (Magri et al., 2009a).

Mercer and Pinder (1974) and Lever and Jackson (1985) suggested Eq. (9) for the dependence of the viscosities on the concentration and