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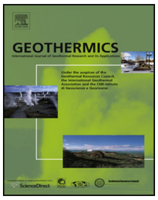

A parametric study of the thermal recharge of low enthalpy geothermal reservoirs

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ABSTRACT

This study finds that the production profile (temperature and longevity) of low enthalpy geothermal reservoirs depends significantly on the thermal conductivity of the confining beds, which recharge the reservoir by conduction. The thermal recharge furthermore is proportional to the production rate and increases dramatically in thin reservoirs, while impermeable reservoir sections have little effect on the production profile. For the Margretheholm geothermal plant, Copenhagen, Denmark, production temperatures are modelled to decrease by only 7 °C–14 °C after 300 years of production due to thermal recharge. The study emphasizes the huge potential of geothermal energy in the development of environmentally sustainable cities.

1. Introduction

The exploration and exploitation of geothermal energy has increased globally within recent decades in the pursuit of sustainable, low carbon emission energy sources (Lund et al., 2011). Low-enthalpy geothermal energy is present in sedimentary basins in large areas worldwide and forms a very large energy potential e.g. for district heating purposes. Energy utilization from sedimentary reservoirs typically focuses on the depth interval 1000–3000 m (e.g. Mahler and Magtengaard, 2010; Lopez et al., 2010). At these depths, the increased temperature and pressure drives the compaction of the pore matrix and the dissolution and precipitation of solutes which alters the pore space in the reservoir. The complex nature of compaction and diagenesis has potential implications for the spatial variation in reservoir permeability and porosity which in turn impacts the advection-driven heat transport during production and injection. Moreover, thermal and hydraulic gradients that form during production and injection stimulate heat exchange between the reservoir and adjacent formations.

Gringarten (1978) studied the heat exchange between geothermal reservoirs and adjacent formations by utilizing simple analytical approximations to estimate the lifetime and recovery of a series of low-enthalpy geothermal reservoirs. Among other findings, he showed that the ratio between the circulation rate and the vertical thermal conductivity of the confining rocks significantly influence the temporal development in production temperatures. In a more recent study, Magtengaard and Mahler (2010) gave reservoir projections for geothermal reservoirs in the Copenhagen area (Denmark) including the Triassic Bunter sandstone which is currently utilized for geothermal energy production. They concluded that heat flow from adjacent formations contribute significantly to the estimated energy resources of the reservoir.

This paper studies the principal components of thermal recharge in a series of conceptual, low-enthalpy geothermal reservoir systems from which warm water is produced. We investigate production temperatures and the thermal interplay between the geothermal reservoir and its confining beds during 300 years of energy production from a doublet well system (combined production and reinjection of the cooled water) by high-resolution finite element modelling. The hydraulic and thermal parameters are inspired by the geothermal characteristics and properties of existing low-enthalpy reservoirs in Denmark. In this paper we explore the sensitivity of production temperatures and the thermal recharge of the reservoir from the adjacent confining beds, to the: (case 1) thermal conductivity of the confining beds (and anisotropy hereof); (case 2) production rate; (case 3) injection temperature; and (case 4) thickness of the reservoir. In case 5, an aquitard of varying thickness separates the reservoir into two permeable sections. The effects of mechanical heat dispersion on production temperatures and thermal recharge are briefly addressed in a separate section. The paper concludes with a case study in which the thermal recharge of the Bunter sandstone reservoir utilized by the

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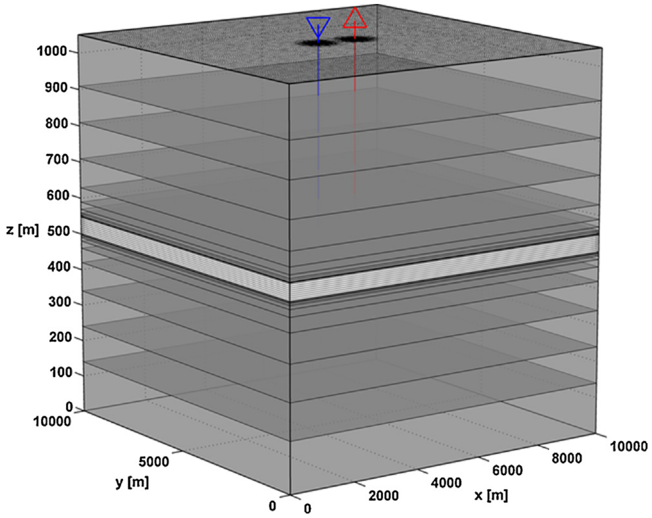

Fig. 1. The (reference) model domain including the reservoir at $z = 500–550$ m (*white*); the confining beds at $z = 0–500$ m and 550–1050 m (*grey*); the injection (*blue, down triangle*) and production (*red, up triangle*) well at $(x,y) = 4400$ m, 5000 m and 5600 m, 5000 m, respectively. Finite element nodes (vertices) are dotted on the upper boundary ($z = 1050$ m). Shown layers correspond to model layers. The vertical scale is arbitrary and serves merely as a reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Margretheholm geothermal plant in Copenhagen, Denmark is estimated.

2. Numerical modelling

The following five subsections describe separately the mathematical formulation of the governing differential equations for reservoir flow and heat transport, boundary conditions, hydraulic and thermal parameters and the spatial and temporal discretization employed in the numerical modelling. Finally, a few essential definitions are provided.

2.1. Mathematical formulation

The density-coupled governing equations for groundwater flow and heat transport in porous media are solved by the finite element model FEFLOW (Diersch, 2009). The physical quantities in Eqs. (1)–(3) are listed in the Glossary section.

$$S_s \frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = Q \tag{1}$$

$$\mathbf{q} = -\mathbf{K} f_\mu \left(\nabla h + \frac{\rho_f - \rho_0}{\rho_0} \mathbf{e} \right) \tag{2}$$

$$(\rho c)_b \frac{\partial T}{\partial t} = \nabla \cdot [(\lambda_b \mathbf{I} + (\rho c)_b \mathbf{D}) \cdot \nabla T] - (\rho c)_f \mathbf{q} \cdot \nabla T + H \tag{3}$$

Eqs. (1)–(3) are solved in three spatial dimensions by the finite element method and the second order accurate Adam–Bashforth predictor-corrector time-marching scheme (Diersch, 2009). FEFLOW's shock capturing upwinding scheme is employed in order to reduce unphysical oscillations in the temperature field near temperature fronts or abrupt changes in the thermal parameters at a minimal amount of numerical dispersion (e.g. at the injection well and at the upper and lower boundary of the reservoir).

2.2. Boundary conditions

The conceptual, low-enthalpy, geothermal reservoir extends 10 km × 10 km horizontally (Fig. 1). The reservoir terminates horizontally in thermal and hydraulic no-flow boundaries. The reservoir is 50 m thick (reference thickness) and bounded by 500 m thick confining beds. The characteristic time $\tau = l^2/\kappa$ gives an indication of the amount of time it takes for a temperature change in the reservoir to propagate the distance $l = 500$ m through the confining beds to the model boundaries. In the present study, τ is greater than 5950 years in all cases. Since the simulated time (300 years) is much shorter, the influence of the boundary conditions on the simulation results is expected to be insignificant.

In all scenarios, geothermal water is produced and subsequently re-injected at a specified temperature by means of a doublet well system. The upper model boundary is represented by a specified temperature of 55 °C and hydraulic head equal to 0 m. The heat flow from the Earth's interior is set equal to 65 mW/m^2 which is a typical value for continental regions (Pollack et al., 1993) and for the regions of sedimentary basins in northwestern Europe (Balling, 1995). Hydraulic no-flow conditions are specified at the lower model boundary ($z = 0$ m). The production and injection wells are spaced 1200 m apart around the centre of the model and are represented by highly conductive, discrete 1D elements (Diersch, 2009). The reference production rate is 150 m^3/h and the reinjection temperature (in the reservoir, not at the surface) is 20 °C (Magtengaard and Mahler, 2010). The initial temperature and hydraulic head distributions are established by steady-state simulation of the natural conditions (assuming background heat flow and no production or specified temperature at the injection well). The initial average temperature of the reservoir is 75 °C in all cases. Temperature, and hydraulic and thermal parameters described in the following are selected with the view of representing typical conditions for deep sedimentary reservoirs and are inspired by the conditions in the Danish area (Balling and Saxov, 1978; Mathiesen et al., 2009; Magtengaard and Mahler, 2010)

2.3. Hydraulic parameters

The permeability of the reservoir is set equal to 0.5 darcy (4.93×10^{-13} m^2), and the reservoir pressure is assumed to be 75 MPa which roughly corresponds to the pressure at 2.5 km depth (Winter, 2001). The pore fluid is a 20 w% NaCl brine with a reference density and dynamic viscosity of 1170 kg/m^3 and 0.0015 kg/s m, respectively, at 20 °C (Batzle and Wang, 1992; Mahler and Magtengaard, 2010, p. 5). Converting from permeability, the reference hydraulic conductivity equates to 4×10^{-6} m/s in round numbers. The reference hydraulic conductivity of the confining beds is set equal to 10^{-11} m/s based on textbook values for shale given by Dominico and Schwartz (1998). The specific storage of the reservoir and confining units is set equal to 2×10^{-6} m^{-1} and was calculated from the porosity and the compressibility of water and rock (Schwartz and Zhang, 2003, p. 74). The relation between fluid density and temperature is given by a 6th order polynomial (Diersch, 2009, pp. 26–30).

2.4. Thermal parameters

The porosity of the reservoir and the confining beds is set equal to 25%, which is based on a general porosity–permeability relationship for the Danish area (Mathiesen et al., 2009). The volumetric heat capacity of the pore fluid is 4.0 MJ/m^3/K (Phillips et al., 1981, p. 45). The matrix volumetric heat capacity of the reservoir and the confining beds is equal to 2.3 MJ/m^3/K (Chesworth, 2008, p. 306; Robertson, 1988, pp. 66, 70, 72). The thermal conductivity of the pore fluid is 0.62 W/m/K as the ability of water to conduct heat decreases slightly with increasing salinity (Phillips et al., 1981, p. 20). The thermal conductivity of the reservoir sandstone matrix is isotropic and is set equal to 6 W/m/K (Robertson, 1988, p. 23).