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The role of thermal conduction in the thermal recharge of low-enthalpy geothermal reservoirs

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ABSTRACT

This paper presents a conceptual study of the role of the conductive heat transfer from the confining beds into a series of low-enthalpy, geothermal reservoirs during energy production from a doublet well system. The results clearly demonstrate the significant role of the thermal conductivity of adjacent formations in the thermal recharge of the reservoir. For a specific example, increasing the matrix thermal conductivity of the confining beds from 1.5 W/m/K to 4.5 W/m/K reduces the decline in production temperature by 35% and increases the conductive warming of the reservoir, relative to total extracted energy, by 34% after 300 years of production. The different cases furthermore exhibit large differences in the penetration of the thermal disturbance into the confining beds. Accurate delineation and model representation of the thermal properties of the confining beds are necessary in order to make reliable estimates of thermal resources and long-term projections of production temperatures.

1. INTRODUCTION

Low-enthalpy geothermal reservoirs constitute a stable source of energy that can supplement existing energy sources such as district heating over the course of decades or centuries.

Geothermal reservoirs constitute highly complex flow systems. Temperature contrasts cause variations in pore fluid viscosity and density while compaction and diagenesis control the permeability and porosity on different spatial scales. Projections on longevity and production temperatures typically rely on model analysis in conjunction with detailed information about the spatial variation in reservoir parameters. In combined production-reinjection schemes, cooled water is reinjected into the reservoir, and thermal and hydraulic gradients form, which stimulates heat exchange between the reservoir and the confining rocks. Gringarten (1978) utilized simple analytical approximations to estimate the lifetime and heat 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 influences 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 and concluded that the heat flow from adjacent formations contribute significantly to the estimated energy resources of the reservoir.

In this study, we investigate the conductive thermal coupling between conceptual reservoirs and their confining beds, inspired by the low-enthalpy reservoirs in Denmark (Balling and Saxov, 1978; Mahler and Magtengaard, 2010). The Danish subsurface is characterised by sedimentary basins containing a number of low enthalpy geothermal reservoirs, mainly of Jurassic and Triassic age. Geothermal plants at Amager (Copenhagen) and Thisted (northern Denmark) have the capacity of supplying the district heating network with up to 14 and 7 MW, respectively, by producing warm porewater from Triassic sandstone reservoirs.

The main objective of this study is to quantify the impact of thermal conductivity of the confining beds on production temperatures and the thermal recharge of the reservoir. Four cases represent different reservoir settings in which the confining beds consist of shale or claystone (less thermally conductive, case A), mixed sedimentary rock of sand, silt and clay with a significant content of quartz (thermally conductive, case C) and some intermediary mix of lithologies (case B). Finally, in case D we investigate the impact of thermal conductivity anisotropy.

The analysis applies high resolution finite element modelling in a state-of-the-art numerical framework. The paper lists first the governing equations of fluid flow and heat transport in porous media. Secondly follows a brief description of the numerical model, boundary conditions and model parameters. Thirdly, details about thermal parameters are provided for the

four cases. Finally, results are presented and conclusions are drawn.

2. METHOD

The analysis is based on numerical modelling of the reservoir flow and heat transport during energy production from a doublet well configuration (Fig. 1). In the simulations, density effects and the temperature dependence of fluid viscosity is taken into account. The Bousinnesq approximation is applied in all simulations. The density-coupled governing equations for groundwater flow and heat transport in porous media (equations [1]-[3] below) are solved by the finite element model FEFLOW (Diersch, 2005).

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

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

$$(\rho c)_b \frac{\partial T}{\partial t} = \nabla \cdot \left[\left(\boldsymbol{\lambda}_\mathbf{b} + n(\rho c)_f \mathbf{D} \right) \cdot \nabla T \right] - (\rho c)_f \mathbf{q} \cdot \nabla T + H \qquad [3]$$

S_s = specific storage [1/m]; h = hydraulic head [m]; t = time [s]; $\mathbf{q}$ = specific discharge vector [m/s]; $\mathbf{K}$ = hydraulic conductivity tensor [m/s]; f_μ ratio between reference dynamic viscosity and dynamic viscosity of the fluid [-]; ρ_0, ρ_f = fluid reference density and fluid density, respectively [kg/m^3]; $\mathbf{e}$ = gravity unit vector [-]; $(\rho c)_f$, $(\rho c)_b$ = fluid and bulk volumetric heat capacity, respectively [J/m^3/K]; T = temperature; $\boldsymbol{\lambda}_\mathbf{b}$= tensor of bulk thermal conductivity [W/m/K]; n = porosity; $\mathbf{D}$ = tensor of mechanical dispersion [m^2/s]; and H is a heat source [W/m^3].

Equations [1]-[3] are solved by the finite element method and a second order accurate Adam-Bashforth time-marching scheme. FEFLOW's shock capturing upwinding scheme is utilised in all simulations.

3. NUMERICAL MODEL

The reservoir extends 10 km x 10 km horizontally and is confined above and below by thick, low-permeable formations. The geometry of the reservoir and the confining beds is identical in all studied cases. The reservoir is penetrated by two wells from which water is produced and subsequently reinjected. The conceptual model of the reservoir is illustrated in Fig. 1.

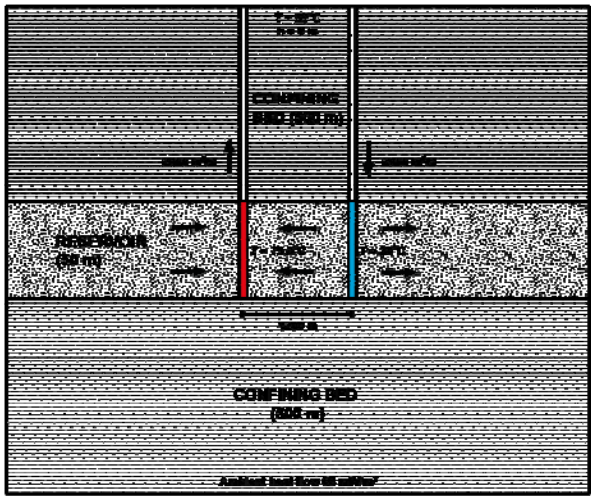

Figure 1: The conceptual model including boundary conditions, wells, reservoir and confining beds. The vertical and horizontal scales are obscured for visualisation purposes (thicknesses are given in parenthesis). Arrows indicate the direction of flow.

The model reservoir is 50 m thick with confining beds of thickness 500 m. The background heat flow from the Earth's interior is 65 mW/m^2 and is applied at the bottom of the model. In case A, the temperature boundary condition at the top of the model is set equal to 50°C. In the remaining cases, the temperature is specified so that the initial average reservoir temperature is identical in the four studied cases. Vertical boundaries are represented by thermal no-flow conditions. Hydraulic no-flow conditions are specified at all model boundaries except at the top where hydraulic head is set equal to zero. Production and reinjection is at a rate of $2.78 \cdot 10^{-2}$ m^3/s (2400 m^3/d) in the two central wells spaced 1200 m apart. The reinjection temperature is 20°C. The initial average temperature of the reservoir is 75.6°C. The wells are fully screened.

The permeability of the reservoir and the confining beds is $4.93 \cdot 10^{-13}$ and $1.23 \cdot 10^{-16}$ m^2 (0.5 and $1.25 \cdot 10^{-4}$ darcy), respectively, which is based on general characteristics of sedimentary rocks and geothermal reservoirs in Denmark (Mahler and Magtengaard, 2010). Specific storage and porosity is set equal to $2.5 \cdot 10^{-6}$ m^{-1} and 25% in the reservoir and the confining beds. The volumetric heat capacity of the fluid and matrix is 4.2 MJ/m^3/K and 2.2 MJ/m^3/K, respectively, in the reservoir and the confining beds. The matrix thermal conductivity of the reservoir is 6 W/m/K. Fluid thermal conductivity is 0.64 W/m/K. Dispersivity is set equal to 20 m and 2 m, respectively, following the guidelines of Gelhar et al. (1993).

Numerical stability is evaluated by the mesh Peclet number, which depends on the spatial discretisation and the dispersivity values employed in the

simulations. The mesh Peclet number is less than 2 in the present simulations as recommended by Voss and Provost (2003).

Time stepping is automatized by the Adam-Bashforth predictor-corrector scheme. The total simulated time is 300 years.

4. CASES

The matrix thermal conductivity (λ_m) of the confining beds is selected with the view of representing typical low, intermediate and high conductivity. λ_m for cases A, B, and C are 1.5, 3 and 4.5 W/m/K, respectively (Balling et al., 1981; Robertson, 1988). The thermal conduction in the confining beds is predominantly vertical and is therefore influenced by anisotropy in the thermal conductivity (horizontal to vertical). Typical values of anisotropy of shale and claystone are in the vicinity of 1.7 (Robertson, 1988). As such, the vertical matrix thermal conductivity of the confining beds in case A can be as low as 0.9 W/m/K. To investigate the impact of anisotropy in the thermal conductivity on production temperatures and heat conduction to the reservoir, the anisotropy of thermal conductivity is set equal to 1.7 in case D. Case D is otherwise similar to case A. The parameter values are summarised in Table 1.

Table 1: The thermal parameters utilised in case A-D. Case D is otherwise similar to case A. λ_m is the isotropic matrix thermal conductivity. $\lambda_{m,xx,yy}$ and $\lambda_{m,zz}$ is the horizontal and vertical matrix thermal conductivity, respectively.

Case	Parameter	Value
A	λ_m	1.5 W/m/K
B	λ_m	3.0 W/m/K
C	λ_m	4.5 W/m/K
D	$\lambda_{m,yy,xx}/\lambda_{m,zz}$	1.70

4. RESULTS

Two parameters, E_p and E_{tr}, are introduced in the following. E_p is defined as the cumulated extracted energy from the production well [J]. E_{tr} is defined as the difference between the cumulated heat flow from the Earth's interior and the actual cumulated heat flow during production, perpendicular to the reservoir boundaries [J]. The latter parameter quantifies the time integrated amount of heat conducted into the reservoir due to the cooling during production. ΔT is the decline in production temperature. The ratio E_{tr} to E_p quantifies the time integrated energy that has been conducted into the reservoir relative to the time integrated energy that has been removed during production.

For reference, an additional simulation was carried out in which the confining beds were replaced by thermal and hydraulic no-flow boundaries (indicated by "No-flow boundaries" in the legend in Figs. 2 and 3).

4.1 Thermal recharge

Figure 2 shows the accumulated thermal conduction to the reservoir relative to total extracted energy (E_{tr}/E_p) in cases A-D.

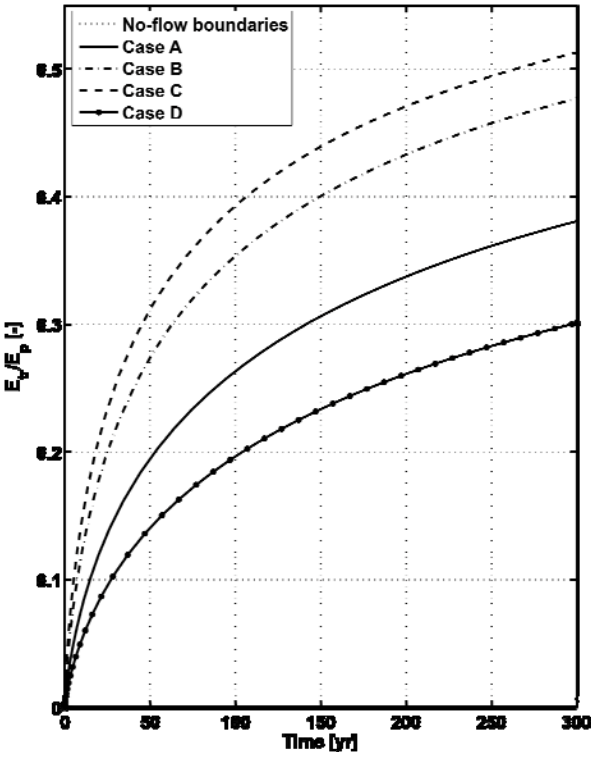

Figure 2: The ratio between the cumulated energy that can be attributed conductive heat flow from the confining beds E_{tr} and the cumulated extracted energy E_p for cases A, B, C, D and assuming no heat exchange between the reservoir and the confining beds ("No-flow boundaries"). The latter obviously is zero throughout the simulated period.

In case A, the ratio E_{tr}/E_p is approximately 0.38 after 300 years of production, while for case B and C, the ratios are 0.48 and 0.51, respectively. Relative to case A, the increase in heat conduction to the reservoir, relative to total extracted heat, is 26% and 34% in case B and C, respectively. Anisotropy in the thermal conductivity further restricts thermal conduction to the reservoir. In case D, the thermal recharge by conductive warming of the reservoir relative to total extracted heat is reduced to 0.3. Relative to case D, heat conduction to the reservoir is increased by 70% in case C. Main results are summarised in Table 2.

Table 2: The decline in production temperatures ΔT and the ratio between the energy conducted to the reservoir and total extracted energy after 300 years of production in case A, B, C, D and assuming no heat exchange between the reservoir and the confining beds ("No-flow").

Case	ΔT [°C]	E_{tr}/E_p [-]
No-flow	20.1	0
A	10.7	0.38
B	8.4	0.48
C	7.0	0.51
D	12.3	0.30

The differences in projected thermal recharge in case A-D clearly demonstrate the impact of the thermal conductivity of the confining beds on the thermal recharge of the reservoir. The increased warming of the reservoir is expected to have consequences for the production temperatures during the 300 year period. In the following, production temperatures in case A-D are compared.

4.2 Production temperature

Figure 3 shows the decline in production temperatures in case A-D.

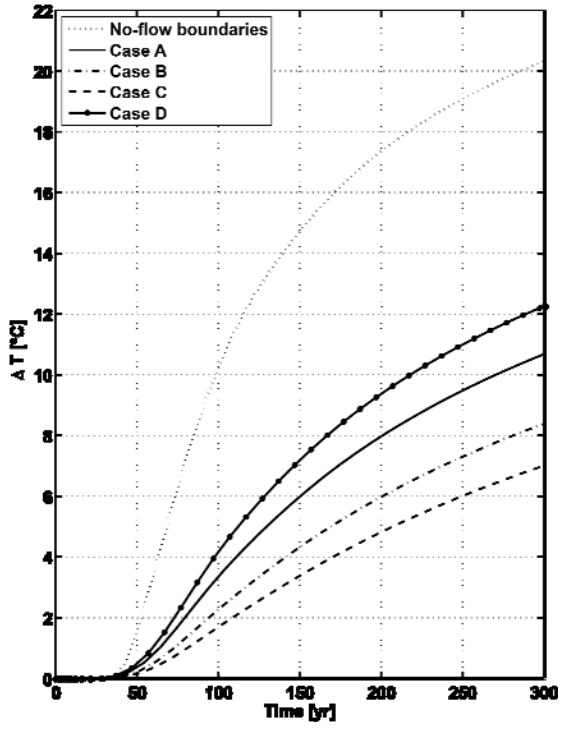

Figure 3: The decline in production temperatures ΔT in case A-D and assuming no heat exchange between the reservoir and the confining beds ("No-flow boundaries"). The thermal injection front arrives at the production well between 40 and 50 years after production start.

The decline in production temperatures during the 300 year period is 10.7°C, 8.4°C, 7.0°C and 12.3°C in cases A, B, C and D, respectively. Replacing the confining beds by thermal and hydraulic no-flow boundaries increases the temperature decline to 20.3°C, which corresponds to a 90%, 142%, 190% and 65% increase relative to Cases A, B, C and D, respectively. Relative to case A, the decline in temperature is reduced by 22% and 35% in cases B and C, respectively. Anisotropy in the thermal conductivity further increases the temperature decline in the production well. In case C, the decline in production temperature decreases by 43% relative to case D.

The increased warming of the reservoir with increasing thermal conductivity of the confining beds significantly influences the decline in production temperatures. The temperature decline, however, is fairly moderate in all the studied cases. This is due to the geometry of the well pattern and the circulation rate applied which, by intent, are designed for sustainable production over the course of several hundred years.

4.3 Temperature distributions

The thermal recharge of the reservoir has implications for the temperature distribution in the confining beds. Vertical temperature profiles at the injection well in case A-D are illustrated in Fig. 4.

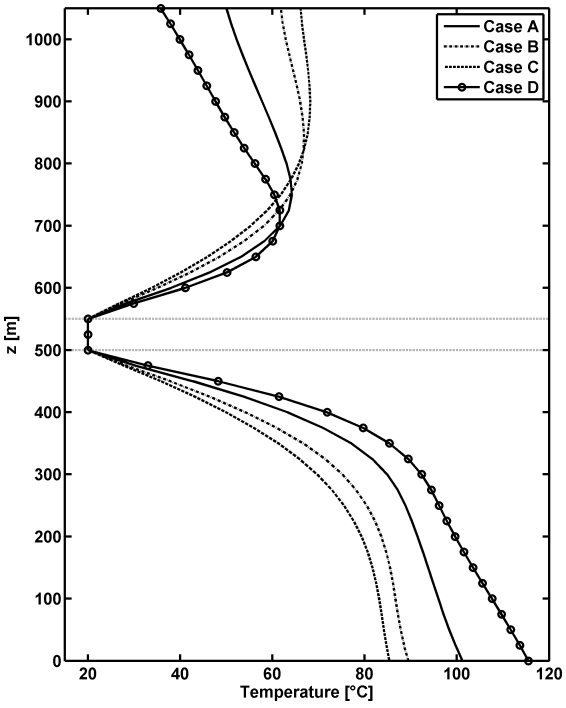

Figure 4: The vertical temperature distribution in the reservoir and the confining beds at the injection well after 300 years of production. The reservoir is indicated by grey, dotted lines. The vertical scale is arbitrary and serves merely as a reference.

The undisturbed linear temperature profiles can be recognised at some distance from the reservoir in case A-D after 300 years of production. The thermal perturbation caused by the injection of cooler water penetrates the confining beds differently in the four cases. In case A, the distance at which the confining beds are thermally disturbed by the injection well is approximately 200 m. The corresponding distances are 270 m and 350 m in cases B and C, respectively. In case D, the distance is approximately 150 m.

Given the time scale considered, the utilisation of the reservoir has implications for the temperature distribution hundreds of meters above and below the reservoir. Therefore, adequate characterization of the thermal properties of the formations in the vicinity (up to a few hundred meters) of the reservoir may be required to capture the long-time thermal recharge of the reservoir.

The horizontal temperature distribution in the confining beds 80 meters below the reservoir boundary after 300 years is illustrated for cases C and D in Fig. 5.

In case C, the temperature decline is close to 35°C in the vicinity of the injection well. In case D, the thermal perturbation is significantly less, just slightly more than 16°C at the injection well. As previously demonstrated, the thermal disturbance of the confining beds increases, as the thermal conductivity of the confining beds increases. The horizontal extent of the temperature depression in the confining beds is reduced as the thermal conductivity of the confining beds increase. The difference is subtle however, as the evolvement in the temperature depression in the reservoir and subsequently in the confining beds is largely controlled by the circulation rate which is identical in the four studied cases. The subtle difference is due to the increased warming of the reinjected water which in turn slows the development of the temperature depression around the injection well and therefore also in the confining beds. The delay in the arrival of the cold front is also observable in the production temperatures (Fig. 3).

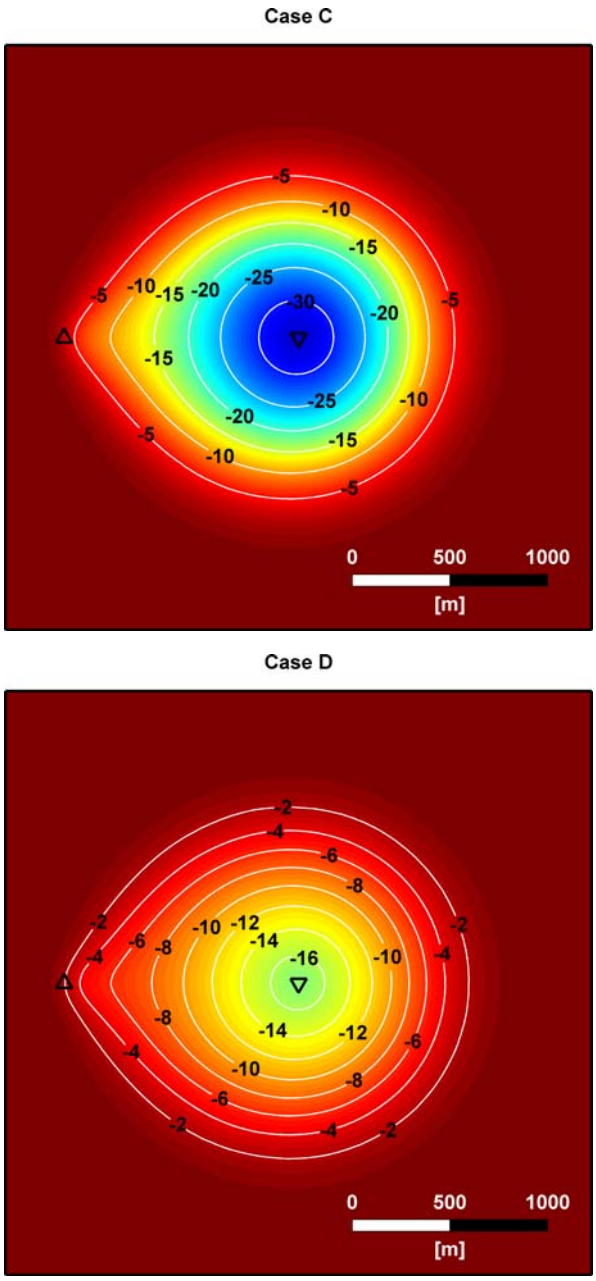

Figure 5: The temperature reduction in the confining beds [°C] in the vicinity of the production- and injection well 80 meters below the reservoir boundary after 300 years in case C and D. Colour scales are identical. The pumping and injection wells are indicated by an up- and down-triangle, respectively.

5. CONCLUSIONS

This paper presents a modelling based study of the thermal coupling between a series of conceptual low-enthalpy geothermal reservoir and their confining beds. The analysis is based on high resolution FEM modelling of density-coupled reservoir flow and heat transport. The results clearly demonstrate the important role of the thermal properties of the confining beds in the thermal recharge of the

reservoirs. In a specific example, given realistic thermal conductivities of the confining beds, the decline in production temperature is reduced by 35% and the conductive warming of the reservoir, relative to total extracted energy, is increased by 34% (case C relative to case A) after 300 years of production. Increased thermal recharge tends to slow the development of the temperature depression in the reservoir. The results further demonstrate the increased penetration of the thermal perturbation into the confining beds as the thermal conductivity of the confining beds increases. Given a high and low thermal conductivity of the confining beds, the thermal perturbation extends 350 m (case C) and 200 m (case A) into the confining beds. As such, accurate delineation and model representation of the geometry and the thermal properties of both the confining beds and the reservoir are necessary in order to make reliable estimates of thermal resources and long-term projections of production temperatures and the profitability of low-enthalpy geothermal plants. Future studies should focus on evaluating the impact of reservoir heterogeneity on the thermal recharge of geothermal reservoirs.

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