Combination of borehole heat exchangers and air sparging to increase geothermal efficiency

Combinaison de sondes géothermiques et barbotage d’air pour augmenter l’efficacité géothermique

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ABSTRACT: Closed and open systems are available for the usage of shallow geothermal energy. In closed systems heat can only be transferred conductively for the case of no groundwater flow. Unfortunately heat conduction is a relatively slow heat transfer mechanism, which causes limited heat-abstraction capacities in geothermal systems. A patented method is presented, in which a closed system is combined with groundwater-circulation technology. In this way a groundwater circulation will be created artificially, which increases convective heat transfer in the soil and therefore the heat capacity of the geothermal system. In this paper a borehole heat exchanger combined with an air sparging well is numerically simulated. The induced groundwater circulation and the heat propagation are calculated sequentially. The heat capacity of this system is compared to a normal borehole heat exchanger. Furthermore, variation calculations are performed to investigate the influence of density of the water-air-mixture in the well, permeability and hydraulic conductivity of the soil. A profitability analysis is carried out based on the numerical results.

RÉSUMÉ : Des systèmes ouverts et fermés sont disponibles pour l’utilisation de l’énergie géothermique peu profonde. La chaleur, présente dans les systèmes fermés ne peut être transférée par conduction s’il n’y a pas un écoulement d’eaux souterraines. La conduction thermique est malheureusement un mécanisme de transfert thermique assez lent. Cela limite donc la capacité thermique dans ces systèmes géothermiques. On présente un procédé breveté où un système fermé est combiné avec une technologie de circulation des eaux souterraines. La circulation des eaux souterraines est artificiellement créée, ce qui permet d’augmenter le transfert thermique par convection dans le sol et, par conséquent, la capacité calorifique du système géothermique. Dans cet article, une sonde géothermique combinée à une injection d’air sont simulées numériquement. La circulation des eaux souterraines induite, ainsi que la propagation de chaleur, sont calculées de manière séquentielle. La capacité calorifique du système est comparable à celle d’une sonde géothermique normale. En outre, des calculs de variations sont effectués afin d’étudier l’influence de la densité de l’eau/air mélangé dans le puits de conductivité, de la perméabilité et l’état hydraulique du sol. Une analyse de rentabilité est ensuite effectuée à partir de ces résultats numériques.

KEYWORDS: shallow geothermal energy, air sparging, induced groundwater flow, numerical simulations

1 INTRODUCTION

Shallow geothermal systems use the energy that is available within the top 400 m of the Earth’s crust. The relatively constant temperatures of the soil can be used to heat or cool buildings.

In closed systems without groundwater flow, heat is transported by conduction only. This is a very slow process and it limits the heat-abstraction capacity of the system. Systems that induce groundwater flow have the advantage of being able to use convection as a much faster heat transfer mechanism (Ma and Grabe 2009, Wang et al. 2009). These are open systems that, in spite of the higher efficiency, are rarely used because permissions for these systems are difficult to obtain. Also the hydrological boundary conditions for these systems can be hard to fulfill and limit the usage of open systems. Alternative methods are possible for closed systems.

Ma and Grabe (2009) suggest the combination of a groundwater-circulation system with a borehole heat exchanger. Several methods exist to induce groundwater circulation. For this example the air-injection well (Wehrle 1990) was chosen. The objective of this entry is to numerically show to what extent the efficiency of borehole heat exchangers can be increased through the use of air-injection at sites with low to zero groundwater flow (Ma and Grabe 2011).

2 NUMERICAL SIMULATION OF AIR-INJECTION BOREHOLE HEAT EXCHANGER

2.1 *System description*

Figure 1 shows the concept of the combined air-injection borehole heat exchanger. In this example the system is coupled with an A/C. Unlike with regular borehole heat exchangers the borehole in this case is not filled with grouting. Instead a drainage layer is installed below the water table and the heat exchanger pipes as well as the air-injection pipe are fitted into the borehole. Above the water table the borehole is sealed, save for a small opening to let the air escape.

For the following calculations summer usage is assumed as well as temperature independent thermal and mechanical characteristics. The results can easily be converted for a winter scenario as long as the fluid in the pipes does not reach temperatures below 0°C.

When the system is in use, air is injected to the lowest point of the well to create an air-water mixture with a density lower than that of the surrounding water. The water level in the well rises higher than the groundwater table. That way water can flow from the well into the aquifer in the top part of the well, while in the bottom part water is flowing from the aquifer into the well.

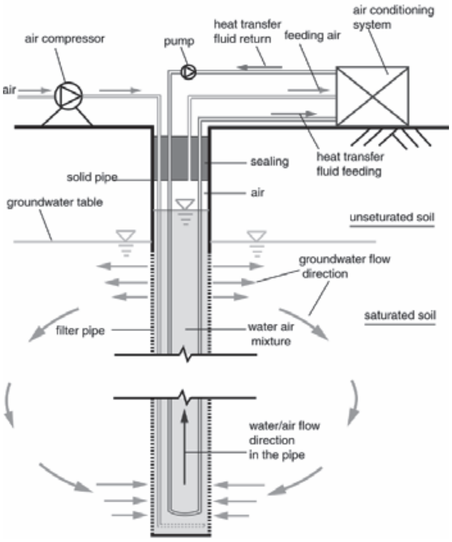

Figure 1. Combination of an air-sparging downhole heat exchanger with an air conditioning system

The combination of a borehole heat exchanger with an air-injection well increases the performance of the system shown in Figure 1 in three ways. First, the groundwater cools the air before it reaches the air conditioning system, therefore reducing the energy necessary for the A/C. Second, the vertical flow of the air-water mixture inside the well increases the heat exchange between the heat pipes and the groundwater (Gustafsson, Westerlund and Hellström 2010). And third, the circulation of the groundwater increases the heat convection in the subsurface which leads to a higher efficiency of the overall system.

2.2 *Numerical model*

The simulations of the air-injection borehole heat exchanger were done with the finite-element program COMSOL multiphysics. A three-dimensional model was used. The geothermal system has a radius of 10 cm and the thickness of the aquifer is 10 m. Prior to the air injection there is no groundwater flow. Four pipes are introduced into the well. The induced groundwater flow, as well as the convective heat transfer are modeled using the FEM. Flow inside the well itself and inside the heat pipes is neglected. The pipes are simplified represented as cylindrical heat sources with constant temperatures.

The aquifer is assumed to consist of homogeneous sand. Several variations concerning heat conductivity, permeability of the soil and density of the air-water-mixture are simulated with the model shown in Figure 2. The used thermal and hydraulic parameters are listed in Table 1. The bold values can be considered to be standard parameters.

Table 1. Applied thermal and hydraulic parameters of the soil and the air-water-mixture

Thermal conductivity sat. soil (W/(m · K))	*1.5/2.0/**2.5**/3.0/3.5*
Specific heat capacity sand (J/(kg · K))	**800**
Effective porosity (-)	**0,25**
Density of water (kg/m³)	**1000**
Density of air-water-mixure (kg/m³)	900/950/980/**990**
Density of sand grains (kg/m³)	**2650**
Permeability (m/s)	10^{-7} ~ $\mathbf{10^{-4}}$ ~ 10^{-3}

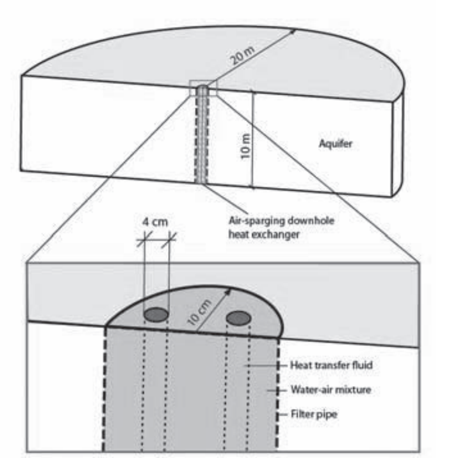

Figure 2. Numerical model for the simulation of an air-sparging downhole heat exchanger

The induced groundwater flow increases heat transport through convection. All calculations assume that the hydraulic and thermal parameters of the soil are temperature independent. This means that groundwater flow is not influenced by heat transport. Both mechanisms – groundwater flow and heat transport – are considered separately. The first step is to simulate the groundwater flow until stationary conditions are reached. The results are saved and in the second step the results are superimposed by the heat propagation in the soil in 90 days.

Before the air injection the well experiences a hydrostatic pressure distribution. As a boundary condition for the simulation the wall of the well experiences a constant pressure distribution from the air-water-mixture, which has a smaller density but a higher water level than the surrounding groundwater. Boundary conditions are shown in Figure 3 (Ma and Grabe 2011).

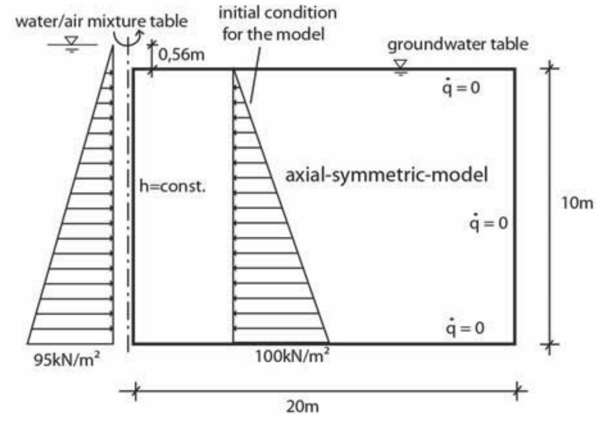

Figure 3. Boundary and initial conditions of the model for calculation of the groundwater circulation caused by air-sparging with an air-water-mixture with a density of 990 kg/m³

3 NUMERICAL RESULTS

3.1 *Groundwater flow*

The groundwater flow induced by the air injection is calculated until stationary conditions are reached. The arrows in Figure 4 show the calculated velocity vectors of the groundwater. The highest velocity (approx. $1.2 \cdot 10^{-5}$ m/s) can be found close to the well. With increasing distance to the well the velocity decreases. The flow lines show the groundwater circulation. The bold parameters from table 1 achieve a water exchange rate between well and soil of about 0.06 m³/h.

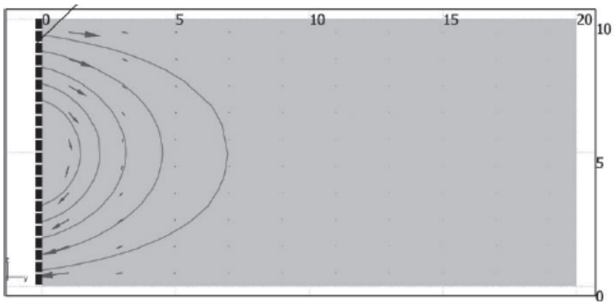

Figure 4. calculated velocity field (arrows) and particle tracing (lines) of the groundwater around the air-sparging downhole heat exchanger at a steady rate ($\Delta\rho$ = 10 kg/m³, k = 10^{-4} m/s)

3.2 *Heat transport*

Without the air injection the heat distribution around the borehole heat exchanger is uniform. The induced groundwater circulation transports heat away from the well and changes the shape of the temperature field. In the upper part of the aquifer the convective heat transport has the same direction as the conductive heat transport. This increases the heat spreading rate, which can be seen from the larger heat plume around the well. In the lower part of the well the groundwater flow direction is opposite the direction of heat conduction, which slows the heat spreading rate. At the bottom of the well the groundwater flow towards the well is so strong that the heat cannot spread outwards anymore.

The overall heat plume around the well is larger when air injection is active. This shows that more heat can be transported into the ground using an air-injection borehole heat exchanger than using a regular borehole heat exchanger.

3.3 *Efficiency of air-injection borehole heat exchanger with standard parameters*

The amount of heat $E(t_n)$ that the borehole heat exchanger transports into the ground at the time t_n equals the integral product of the temperature change along the entire body of soil with a soil density of ρ_B and the specific heat capacity c_B:

$$E(t_n) = \int \rho_B c_B \, [T(x,y,z,t_n) - T_0] dV \qquad (1)$$

The specific heat abstraction capacity per meter heat exchanger $P_s(t_n)$ is time-dependent:

$$P_S(T_N) = \frac{E(t_n) - E(t_{n-1})}{l \cdot (t_n - t_{n-1})} \qquad (2)$$

In this case l is the length of the borehole heat exchanger.

Figure 5 shows the specific heat abstraction capacity as a function of time, comparing a regular borehole heat exchanger and one that uses air injection. In both systems the heat abstraction capacity rapidly reduces within 20 days and changes only minimally afterwards.

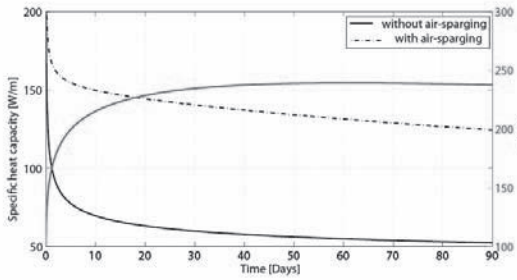

Figure 5. Calculated specific heat capacity with and without air sparging and efficiency increasing rate of the downhole heat exchanger compared with normal downhole heat exchanger ($\Delta\rho$ = 10 kg/m³, λ = 2.5 W/(m · K), k = 10^{-4} m/s)

3.4 *Variation calculations*

During the calculations three parameters were varied: density of the air-water-mixture inside the well, heat conductivity and permeability of the soil.

For low permeabilities of the soil (k < 10^{-5} m/s) the heat abstraction capacity depends only on the thermal conductivity of the soil. In permeable soils (k > 10^{-4} m/s), convection is the dominant heat transport mechanism and heat conduction has no influence. In between those parameters the heat abstraction capacity depends on permeabilty as well as on thermal conductivity.

The influence of the air injection depends on the ratio between thermal conductivity and induced convection. The decisive factor for thermal conductivity is the specific thermal conductivity of the soil (λ). The convection depends on the median groundwater circulation velocity (v_z) that can be calculated using Darcy's law.

$$v_z = k \cdot i \qquad (3)$$

Assuming a constant median flow distance the following relationship can be applied:

$$v_z = c \cdot k \cdot \Delta\rho \qquad (4)$$

Here, c is a constant. The efficiency increasing rate (η) is therefore mainly dependent on the three parameters k, λ and $\Delta\rho$. The relationship between η and λ shows that the five curves in Figure 6 fit very well when η is mutlilied by $\lambda^{0.7}$. The relationship between η, λ, k and $\Delta\rho$ is shown in Figure 7. The y-axis is labeled $\eta \cdot \lambda^{0.7}$ and the x-axis is labeled k · $\Delta\rho$. All calculated points can be converged towards the adaptation curve.

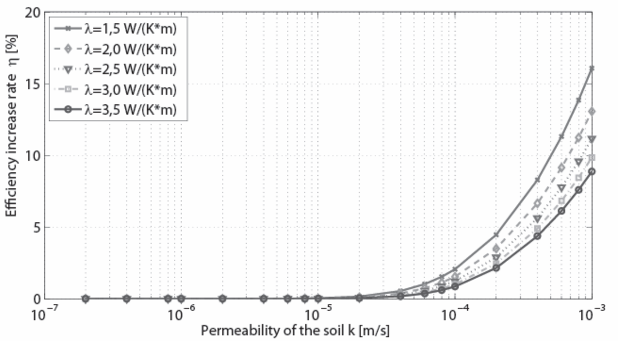

Figure 6. Calculated efficiency increasing rate of the air-sparging downhole heat exchanger against the conductivity and permeability of the soil ($\Delta\rho$ = 10 kg/m³)

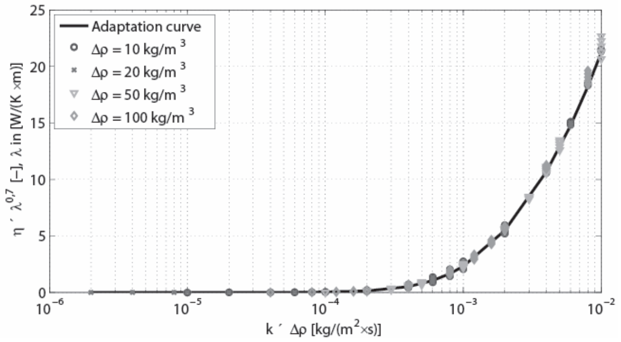

Figure 7. Presentation of the results of the variation calculations and the adaptation curve, x-axis: k · $\Delta\rho$, y-axis: $\eta \cdot \lambda^{0.7}$

This phenomenon offers the possibility of estimating the efficiency increasing rate when the three parameters λ, k and $\Delta\rho$ are known.

4 PROFITABILITY ANALYSIS

To achieve a pressure difference between the well and the surrounding groundwater it is necessary to inject air into the well with an air compressor, which uses electricity. An air-injection borehole heat exchanger is only profitable when the increase of the heat abstraction capacity is higher than the energy used by the air compressor.

To calculate the energy necessary for the air compressor to work, two parameters are needed: operating pressure and air flow rate.

To calculate the injected air a perfomance record is chosen, which considers not only effective power for water production and air expansion but also includes a performance loss ratio (Rautenberg 1972):

$$N_L \pm N_W + N_R + N_S + N_B + N_{E,U}$$

With

N_L	air expansion
N_W	effective power for water production
N_R	dissipation loss due to friction of the two-phase flow
N_S	dissipation loss due to slip between air bubbles
N_B	dissipation loss to accelerate the water
$N_{E,U}$	entry and exit dissipation loss

The dissipation loss $N_{E,U}$ is very small compared to the other factors and can be neglected.

By iteratively solving equation 5 the necessary air flow rate for inducing a groundwater circulation can be calculated. For a density of $\Delta\rho = 10$ kg/m³ the through air injection induced water flow rate is so low that effective power for water production can be disregarded. The amount of air necessary for achieving a pressure gradient in the well, which is the minimally necessary air flow rate (Luber 1999) and does not depend on soil permeability, is the decisive factor for calculating the total amount of air. This leads to a small-scale dependency of the total amount of air from the soil permeability.

Up until a permeability of $4 \cdot 10^{-5}$ m/s the coefficient of air injection (COA) is smaller than 1, which means that the amount energy used for air injection is higher than the increase in the heat abstraction rate and the use of the air injection technique is not favorable. With increasing k the COA also increases. In a soil with a permeability of $k = 10^{-3}$ m/s, the COA is expected to be about 100. In this case the 100 times of the energy used for the air compressor is converted into usable energy for air conditioning.

The coefficient of performance (COP) for ground coupled heat pumps can reach a maximum of 5 (Pahud and Hubbuch 2007, Wood, Liu and Riffat 2009). This value can already be exceeded by the COA-value of the air-injection borehole heat exchanger with a value for $k = 6 \cdot 10^{-5}$ m/s. In a permeable soil the COA shows the profitability of the air-injection borehole heat exchanger.

5 CONCLUSIONS

Combining an air-sparging well with a borehole heat exchanger offers the opportunity of increasing the heat-abstraction capacity of closed geothermal systems without pumping groundwater. The induced groundwater circulation accelerates the heat transfer through convection.

For a permeability of $k < 10^{-5}$ m/s, the induced circulation is too slow to have an effect on the heat transfer. But with increasing permeability the positive effect of the air injection increases as well. In soils with $k > 10^{-4}$ m/s convection is the dominant method of heat transfer. For soils with $k = 10^{-3}$ m/s and $\lambda = 2{,}5$ W/(m · K) the heat abstraction capacity can increase about ten times through use of air injection when $\Delta\rho = 10$ kg/m³.

Simulations so far have only been done for one air injection borehole heat exchanger and one operating period. Long term simulations as well as an in-situ test in Hamburg are planned (Ma und Grabe 2010).

With certain groundwater chemistries the use of this technique can lead to the sedimentation of iron ochre over time. This may lead to the necessity of cleaning the well with suitable methods (Herth and Arndts 1995). An alternative for this would be the usage of different gases like N_2 or CO_2. In those cases the air escaping the well should be collected and reused.

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