

Modeling of Usage of Air Injection Well in a Geothermal System

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Abstract: Natural groundwater flow can increase the efficiency of geothermal system. But groundwater flow is not available everywhere. A patented new idea is to use air injection well to create artificial flow in sandy or gritty soils. The governing equations of fluid flow and heat transfer problem were solved with the COMSOL Earths Science module.

Keywords: Air injection well, geothermal system, optimization, efficiency increasing.

1. Introduction

Shallow geothermal energy has been widely used as regenerative energy for building heating and cooling all over the world. The worldwide mostly used geothermal system is borehole heat exchangers (1). According to VDI-guideline for thermal use of the underground (2), the heat extraction/injection capacity of borehole heat exchangers can be increased significantly, if there is strong groundwater flow. Numerical simulations have also shown that groundwater flow can raise the efficiency of soil heat exchangers vastly (3).

Viernickel (4) has developed a technology to induce artificial groundwater circulation. A borehole is divided into 2 parts by a seal layer. This so-called “active borehole” uses a water pump in the borehole and lift water from the lower into the upper region. A groundwater circulation is generated around the borehole (**figure 1**).

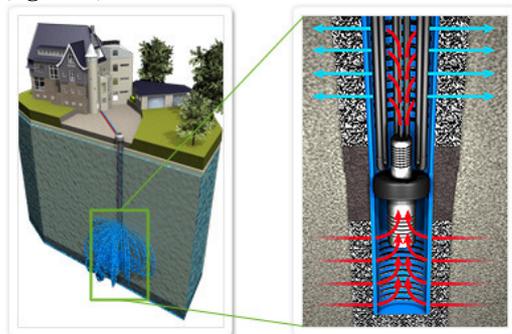


Figure 1: Principle of active borehole (2)

In this paper another technology to generate artificial groundwater circulation is introduced, which combines air injection well with a borehole heat exchanger.

An air injection well is an in situ soil decontamination method for saturated soils. The operation induces a circulating flow in the aquifer due to the injection of pressurized air at the deepest point of a filter pipe (5).

Air injection into a well generates a mixture of water and air having a lower density than surrounding groundwater. In order to gain a pressure equilibration, the table of the water/air mixture must be higher than the groundwater table (**figure 2**). Comparing the fluid pressure in the injection well with the aquifer, an over pressure dominates the upper region of the well, while a under pressure is generated at the bottom of the well (**figure 3**). The pressure difference causes that fluid at the top of the well flows outwards and that groundwater is forced through the filter pipe into the well in the deeper region. Around the well a circulation is induced. The exhaust air out of the well can be used as feeding air into air conditioning or heating system.

The usage of air injection wells can improve the efficiency of geothermal systems in the following ways:

- groundwater circulation enhances the convective heat transfer in the soil,
- circulation of water/air mixture in the well accelerates heat exchange between U-tubes and groundwater,
- feeding air to the air conditioning/heating systems is pre-cooled or pre-heated.

The first way of efficiency increasing is investigated numerically. The other two have also their contribution and are however not component of this paper.

The groundwater circulation as a result of air injection and the conductive and convective heat transfer is simulated with Finite-Element-Method. Flow of water/air mixture in the well is not considered in model.

The well is simplified as a boundary with constant hydraulic pressure for fluid flow model. The induced groundwater flow velocities are

very small, so that they can be described by Darcy's law

$$\mathbf{v} = -(\nabla p - g\hat{e}) \quad (1)$$

where \mathbf{v} is the groundwater flow velocity, \mathbf{K} is a tensor of permeability, ∇p is the pressure gradient vector, g is the acceleration due to gravity, \hat{e} is the unit vector in the vertical direction, pointing downwards and ρ is the density.

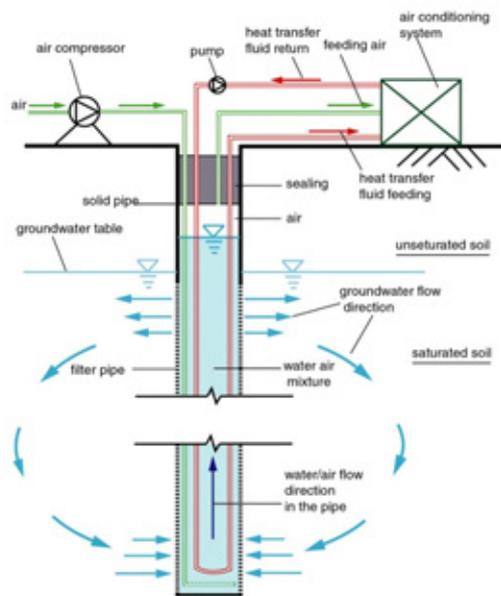


Figure 2: Combined air injection well with a borehole heat exchanger and air conditioning system

The heat propagation in saturated soils with groundwater movement is a combination of conduction and convection. If thermal properties like heat conductivity λ , heat capacity c as well as heat source doesn't depend on the temperature ϑ , the differential equation can be written as

$$\underbrace{\left(\rho \cdot c \right) \frac{\partial \vartheta}{\partial t}}_{\text{Time change}} = \underbrace{\text{div} \left(\lambda \cdot \text{grad } \vartheta \right)}_{\text{Conduction}} - \underbrace{\mathbf{v} \cdot \text{grad } \vartheta}_{\text{Convection}} + \underbrace{\dot{w}}_{\text{Heat source}} \quad (2)$$

The velocity field \mathbf{v} reads from the solution of equation 1.

The governing equations of groundwater flow and heat transfer in subsoil are solved numerically with the Finite-Element-Method

COMSOL, which has been already widely used for simulation of shallow geothermal systems (6, 7). The calculations are performed by parallel computers in Hamburg University of Technology.

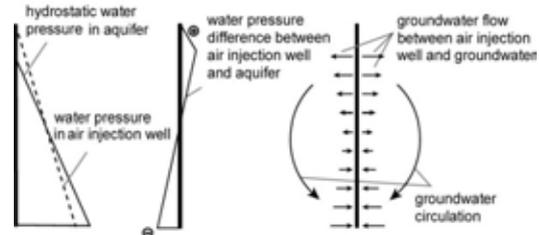


Figure 3: Distribution of water pressure and difference between air injection well and aquifer (left and middle), water flow direction (right)

2. Numerical Simulations of Air Injection Wells

2.1 Basis System

The fundamental model is based upon a combined air injection well with a borehole heat exchanger for a summer operation. Dependent on demand, the air injection well can be activated and deactivated. The simplified system had a 10 m deep homogenous aquifer between two aquitards (figure 4). Pore space of the aquifer is saturated with groundwater, which is unconfined. The borehole above and below the aquifer is fulfilled with backfill material. The air injection well with a radius of 10 cm can influence groundwater flow and therefore heat transport only in the aquifer layer, so the two aquitards are not components in the numerical model.

2.1 Model Buildup

Due to complexity, the heat distribution and 2-phases fluid flow within the air injection well is not considered in the model. The air injection well is simplified as a canulate cylinder, whose wall is a boundary of the system and had constant temperature and water pressure. The system is then axial symmetric and can be simulated with axial-symmetric-model.

The density of water in subsoil amounts 1000 kg/m³, while in the borehole (serves also as air injection well) it decreases to 900 kg/m³ in the basic model as a result of air injection. The

table of water/air mixture reaches 0.56 m above the surrounding groundwater table, in order to gain pressure equilibration. The pressure distribution caused by water/air mixture on the wall of borehole is constant during the simulation and acts as a boundary condition on the left side of the borehole for the fluid flow calculation. On the right side of the wall, a hydrostatic water pressure governs the boundary.

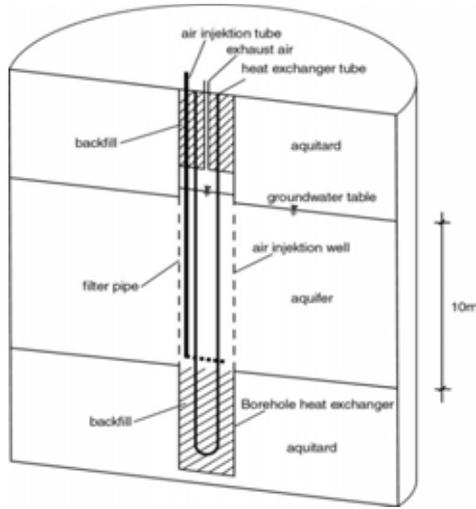


Figure 4: Considered system for the simulation of usage of air injection well in a borehole heat exchanger

There is no water exchange on the right boundary as well as between aquifer and aquitards at the top and bottom of the model (**figure 5**). Soil properties are taken from **table 1**.

The groundwater flow influences heat transfer in subsoil, but not in the opposite direction. It is not necessary to couple the two physics. COMSOL offers the possibility to consider the two physics sequentially, which suffices in this case and reduces calculation expense dramatically.

The groundwater flow and heat transfer are simulated separately. In the first step, Darcy's law fluid flow module in COMSOL is used to calculate the by air injection induced circulation flow of groundwater. After a steady state is arrived, the groundwater flow velocity field is saved and imported into heat transfer model, which is monitored over a period of 90 days.

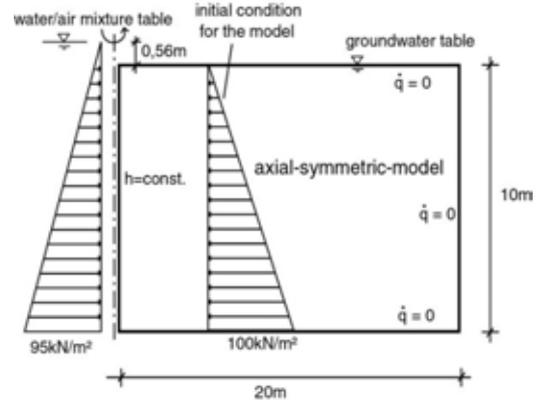


Figure 5: Axial-symmetric-model with boundary and initial conditions

Summer operation is investigated using this model. The injection well is simplified as a cylindrical heat source with a constant temperature, which means, that heat will be injected through the whole shaft surface of the borehole. This improves heat transfer velocity and causes an increasing of heat injection capacity both for the models with and without air injection well (7, 8). This effect is not relevant for the consideration of the relative efficiency increasing because of air injection well, if relative increasing factor is used:

$$f_{aiw} = \frac{\bar{P}_{s,aiw} - \bar{P}_{s,no}}{\bar{P}_{s,no}} \quad (3)$$

where $\bar{P}_{s,aiw}$ and $\bar{P}_{s,no}$ is the average heat injection capacity with and without air injection well. The boundary conditions for heat transfer of the model are

$$\vartheta = 20^\circ\text{C} \quad \text{at the wall of air injection well and}$$

$$\text{grad } \vartheta = 0 \quad \text{for all other boundaries.}$$

The subsoil has an initial temperature of 10 °C.

Table 1: Hydraulic and thermodynamic soil properties for basic model

Thermal conductivity (k)	2.53 W/(m•K)
Specific heat capacity (c)	1750 kJ/(kg•K)
Drainable porosity (n)	0.35
Density (ρ)	2100 kg/m ³
Hydraulic conductivity	1×10^{-5} m/s

Variation calculations with different hydraulic and thermodynamic parameters are also carried out. The capacity of combination of

COMSOL with Matlab offers an opportunity for easy change and performance of variation calculations.

3 Simulation Results

3.1 Groundwater Circulation

Originally, groundwater in the model doesn't flow, because there is no hydraulic gradient. After activation of air injection well, the higher table and lower density of water/air mixture in the well caused pore water pressure change on the left side of model. The fluid flow is then calculated until steady state is reached.

The pressure on the upper of this region is elevated, while it's reduced on the bottom. This pressure change generates a groundwater circulation (Figure 6).

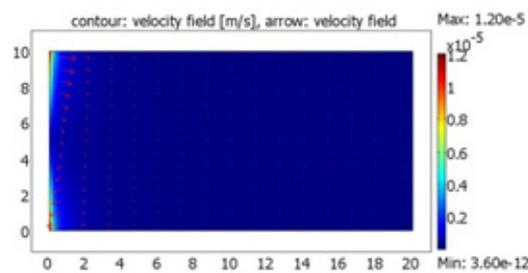


Figure 6: Groundwater flow velocity field around an air injection well

The maximal flow velocity (ca. 1.2×10^{-5} m/s) appears outside of the well-top and -bottom. It drops very quickly with increasing distance to the well. The arrows show the flow direction. Water flows out of the well from the upper region and then in a form of half ellipse to the left-bottom region of the model and finally flows from there into the well again.

3.2 Heat Propagation in Subsoil

With resting groundwater, heat can only be transferred conductively. Due to constant thermodynamic soil parameter, the contour of temperature is homogenous (figure 7).

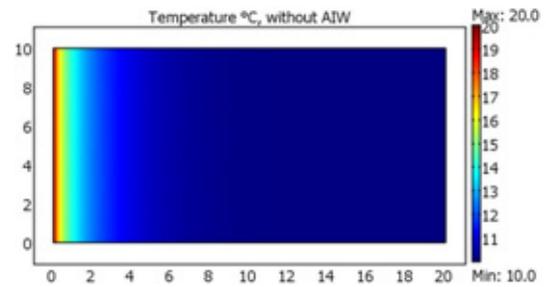


Figure 7: Temperature field without air injection well after a heat injection period of 3 months

The induced groundwater circulation as a result of activation of the air injection well increases convective heat transfer in subsoil. Figure 14 shows the temperature field after a period of 90 days. In the upper region, heat propagates with flowing groundwater down right. The transfer velocity is higher than only with conduction. On the lower region, groundwater flows towards the well. Convective heat transfer is in versus direction of conduction. Therefore heat propagation in this region is slowed down.

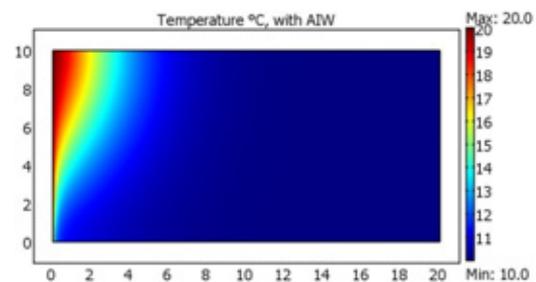


Figure 8: Temperature field with air injection well after a heat injection period of 3 months

The comparison of figures 7 and 8 makes it clear that the total injected heat with air injection well is more than without it.

3.3 Specific Heat Injection Capacity

The total injected surface heat quantity $e_h(t)$ in kWh/m after a certain time t can be calculated using the equation:

$$e_h(t) = \int_{\Omega} c[T(t) - T_0]dA \quad (4)$$

where T is the temperature, dA is the element area. The volume heat quantity $E_h(t)$ in kWh can be deduced from the integration of axial-symmetric-

model to 3D-model. The specific heat injection capacity $P_s(t)$ is a time dependent value. It can be computed with the equation

$$P_s(t_n) = \frac{E_h(t_n) - E_h(t_{n-1})}{l \cdot (t_n - t_{n-1})} \quad (5)$$

where l is the length of the borehole heat exchanger in the aquifer.

Figure 9 shows the time dependent specific heat injection capacity of the borehole heat exchanger. Under continual operation, the temperature difference between borehole wall and surrounding soils decreases with time and therefore the injection capacity. The influence of air injection well (AIW) on the heat injection capacity increases in the first days and then keeps almost constantly.

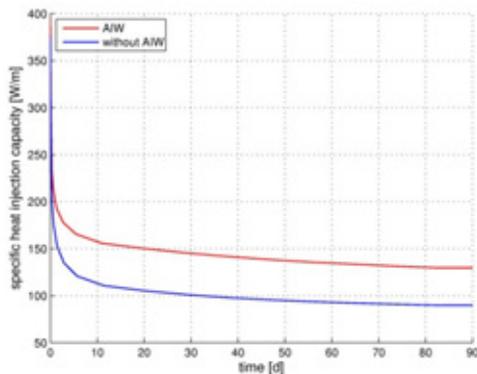


Figure 9: Calculated time dependent specific heat injection capacity with and without air injection well over a period of 90

The numerical simulations show that under the above-mentioned condition the relative increasing factor f_{aiw} amounts 50%.

Several variation calculations with different hydraulic conductivity and water/air mixture density are also performed over a period of 90 days. The relative efficiency increasing factor is presented in **figure 10**. At a hydraulic conductivity (k_f) smaller than 10^{-6} m/s, the installation of air injection well doesn't bring any significant advantage. With growing hydraulic conductivity the influence of air injection well increases. In middle sand, which has a typical k_f of 10^{-4} m/s, the heat injection rate can be enhanced up to 1000%.

Lower density of water/air mixture in the injection well causes bigger pressure difference on the surface of the well, which results faster groundwater circulation and therefore higher

efficiency increasing factor. On the other hand, more energy will be needed for the air injection pump to gain a lower density of water/air mixture.

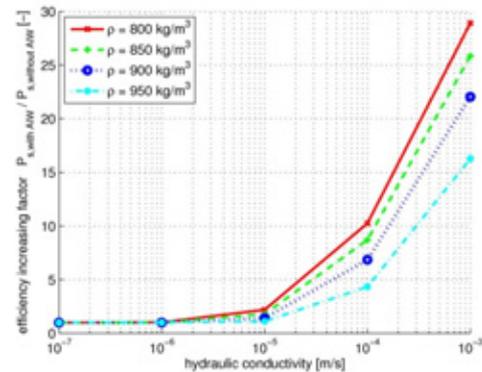


Figure 10: Calculated relative efficiency increasing factor in dependent of hydraulic conductivity and water/air mixture density

4. Conclusions

The fluid flow and heat transfer of a borehole heat exchanger combined with an air injection well is calculated sequentially using the package Earth Science of the Finite-Element-Code COMSOL. The equation of Darcy' Law was firstly solved to achieve the groundwater circulation velocity under steady state as a result of the activation of air injection well. In the second step, the saved flow velocity was imported as initial conditions for the transient heat transfer simulation.

The results of the simulations show that the combination of air injection well in borehole can improve the heat injection capacity vastly. Laboratory and field tests are planned, in order to verify the numerical results.

5. References

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6. Acknowledgements

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