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Open-loop geothermal heating by combined extraction–injection one-well systems: A feasibility study

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ABSTRACT

The feasibility of combined extraction–injection one-well systems for geothermal groundwater utilization was evaluated by means of a numerical parameter study. One-well systems require little space, but it is critically important to avoid circulation flow resulting in a thermal short circuit. Numerical models of groundwater flow and heat transport were performed to check the influence of various hydrogeological and technical parameters. Results show that circulation flow can be avoided in most cases, mainly when hydraulic gradients and conductivities are high and when the distance between the two well screens is sufficient. One-well systems are thus favourable options in urban sand-and-gravel aquifers.

1. Introduction

The use of shallow geothermal energy by closed-loop ground coupled heat pumps or open-loop groundwater heat pump systems is considered to significantly reduce primary energy consumption for heating, to save fossil fuels and to produce less CO_2 emissions (Blum et al., 2010; Lund et al., 2011).

Although open-loop geothermal systems have potential advantages in terms of energy efficiency and environmental impact (Lo Russo et al., 2012), they are still less widespread than closed-loop geothermal systems. Among other reasons, such as the higher demands regarding aquifer characteristics and groundwater chemistry, one important disadvantage of open-loop systems is the required space, since there has to be a particular minimum distance between extraction and injection wells to avoid a thermal short circuit resulting from a hydraulic short circuit (Banks, 2009). This aspect becomes more and more important due to the limited space in densely populated urban areas.

A possibility to minimize or eliminate this problem could be a one-well-system, where the extraction and injection wells of the open-loop-system are replaced by two hydraulically separated well screens placed at different depths within one well. This would also have the advantage of reduced costs and negligible drawdown, because the withdrawal pumping rate equals the injection pumping rate at any moment in time, and the cone of depression and the cone of recharge superimpose to zero. One-well systems were originally designed as groundwater circulation wells (GCW) for the remediation of contaminated sites and have been successfully used for some decades (Herrling et al., 1991; Miller and Roote, 1997; EPA US, 1995, 1998). The functional principle of a GCW is a hydraulic short-circuit between the well screens, resulting in a circulating flow field around the well and therefore leading to a constant and increased remediation without the negative effects of drawdown and abstraction of polluted water. Several studies have shown that the formation of a circulation flow field for remediation depends on aquifer properties, such as horizontal and vertical hydraulic conductivity, natural hydraulic gradient and aquifer thickness, but also on well design, i.e. distance and length of the screens, and on pumping rate (Philip and Walter, 1992; Herrling and Stamm, 1992; Scholz et al., 1998; Scholz, 2000; Peursem et al., 1999; Johnson and Simon, 2007). This implies in turn that the formation of a circulation flow field can be avoided under specific hydrogeological conditions and/or with some technical modifications of the well, so that combined extraction–injection one-well systems could be suitable for thermal use.

Therefore, the purpose of this study was to evaluate the feasibility of combined extraction–injection one-well systems for geothermal purpose, under various hydrogeological conditions, ranging from moderate to high hydraulic conductivity ($K = 10^{-5}$–10^{-3} m/s) and from low to moderate hydraulic gradients ($I = 0.1$–$2‰$), as they are typically found in alluvial aquifers (Fetter, 2001). This was realized by numerical modelling of groundwater flow and heat transport with the finite element software FEFLOW (Diersch, 2013). Based on these schematic models, a set of easy-to-use diagrams was established, to help practicing hydrogeologists and heating engineers in the planning process. Hydraulic

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short-circuit also depends on the technical quality of the well construction. Inappropriate construction of the annular space can cause hydraulic short circuit (Chesnaux et al., 2006), but this aspect was not further evaluated in this feasibility study.

2. Methods

2.1. Conceptual model

Four key parameters, which were supposed to display a significant influence on the occurrence of a circulation flow field, were further tested in this study: the natural hydraulic gradient *I*, the horizontal hydraulic conductivity *K*, the anisotropy factor AF (quotient of horizontal and vertical hydraulic conductivity), and the pumping rate *Q*.

According to Darcy's law, the hydraulic gradient *I*, the hydraulic conductivity *K*, and the pumping rate *Q* strongly affect the flow velocity, at which water is drained from the injection screen or pumped from the production screen. Since a circulation flow has a horizontal as well as a vertical flow component, the anisotropy factor AF of *K* also plays an important role. The vertical distance of the screens *d* affects the time until a short circuit at a given flow velocity would occur. Additionally, the screen lengths affect the spatial dimensions of the capture zone of the production screen and the plume of the injection screen.

Fig. 1 shows a conceptual model of a combined extraction–injection one-well-system, with two hydraulically separated well screens placed in different depths within one well. The natural hydraulic gradient *I*, hydraulic conductivity *K*, and vertical distance of screens *d* are predetermined or limited by the hydrogeological settings. The pumping rate *Q* is prescribed by the given heat demand. This means that these parameters ultimately determine if a thermal use with a combined extraction–injection one-well-system on a specified site and for a specific heat demand is feasible or not. The ranges of feasible parameter combinations were determined by means of a numerical parameter study.

2.2. Parameter study

The implementation of the conceptual model was designed as a schematic numerical groundwater flow and heat transport model with the finite element (FE) groundwater modelling software FEFLOW.

Various parameters must be chosen within a reasonable range to create, on the one hand, the most unfavourable conditions for a thermal use (in the following referred to as "worst case model"), and on the other hand, the most favourable ones ("best case model"). As both represent thresholds, they serve to determine under which conditions a thermal use is generally possible or not. To determine the influence of different parameters regarding the suitability for thermal use, a preliminary parameter study was executed. The evaluated parameters are described in the following paragraphs.

2.2.1. Injection temperature

First of all, the temperature of the re-injected water was evaluated. For simplicity, a year-round constant heating was adopted. In principle, there are two possibilities to implement the injection temperature in models of groundwater heat pump (GWHP) systems: thermal feedback and thermal recycling (Banks, 2009). Thermal feedback assumes that the temperature at the injection well remains constant, even after a short circuit with the arrival of the thermal plume at the production well. Although this assumption ignores the operational mode of heat exchangers, which is linked to a temperature difference between the production and extraction well, it is widely used in modelling GWHP design approaches, due to its mathematical simplicity. Since this simplification simulates more favourable conditions, it is used in the best case models. Thermal recycling does consider the thermal short circuit by coupling the injection and production temperatures. This has been first described mathematically by Milnes and Perrochet (2013), by assuming a constant temperature difference ΔT across the heat exchanger between the production and injection well. Since this approach represents more unfavourable conditions, it is used in the worst case models. In both numerical models the injection temperature was implemented by defining a Dirichlet-type heat boundary condition at the injection well screen.

2.2.2. Minimum production temperature

The second step of differentiating the two models was to define how low the production temperature T_P may descend until a thermal use is no longer energy-efficient. For this purpose, a so called "critical thermal short circuit" was defined. To find a realistic definition of this critical thermal short circuit, technical heat pump data were used (Novelan WIC series, ait-deutschland GmbH, Kasendorf, Germany). Here, a linear correlation between the given maximum pumping rate Q_{max} and the "reservoir power" P_{res} was observed (Fig. 2). P_{res} represents the amount of energy per time unit, which

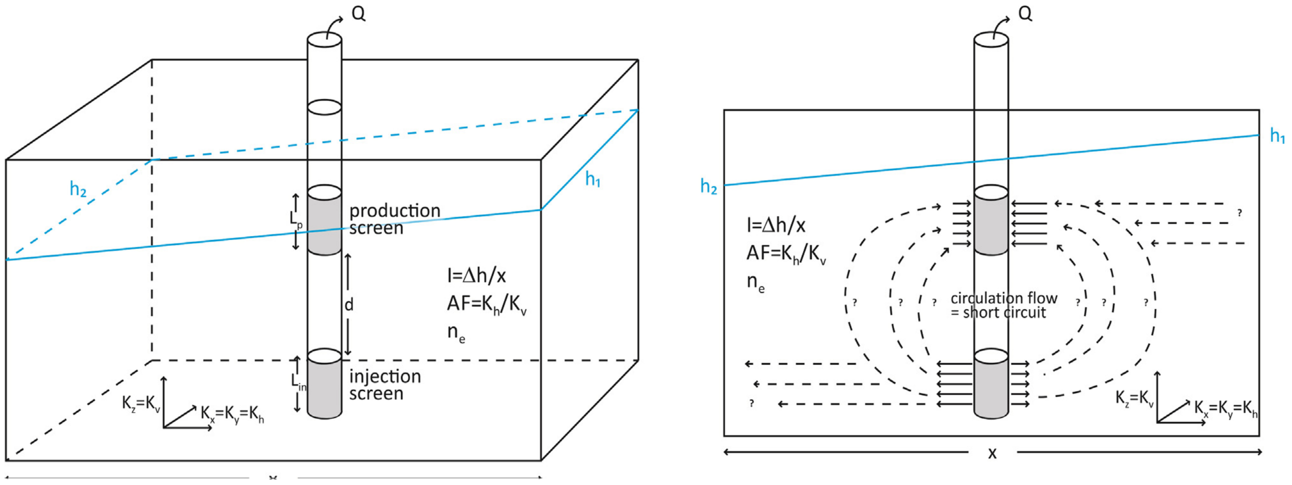

Fig. 1. Conceptual model of a combined one-well-system, with two hydraulically separated well screens placed at different depths within one well. The occurrence of a circulation flow has to be avoided, as it would cause a thermal short circuit when using the well as an open-loop geothermal system. The flow pattern is essentially affected by *I*, *K*, *Q*, *d*, and several other hydraulic parameters. The numerical model used for this study is based on this conceptual model (i.e. same geometry).