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Efficiency of closed loop geothermal heat pumps: A sensitivity analysis

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ABSTRACT

Geothermal heat pumps are becoming more and more popular as the price of fossil fuels is increasing and a strong reduction of anthropogenic CO_2 emissions is needed. The energy performances of these plants are closely related to the thermal and hydrogeological properties of the soil, but a proper design and installation also plays a crucial role. A set of flow and heat transport simulations has been run to evaluate the impact of different parameters on the operation of a GSHP. It is demonstrated that the BHE length is the most influential factor, that the heat carrier fluid also plays a fundamental role, and that further improvements can be obtained by using pipe spacers and highly conductive grouts. On the other hand, if the physical properties of the soil are not surveyed properly, they represent a strong factor of uncertainty when modelling the operation of these plants. The thermal conductivity of the soil has a prevailing importance and should be determined with in-situ tests (TRT), rather than assigning values from literature. When groundwater flow is present, the advection should also be considered, due to its positive effect on the performances of BHEs; by contrast, as little is currently known about thermal dispersion, relying on this transport mechanism can lead to an excessively optimistic design.

1. Introduction

Ground Source Heat Pumps (GSHP) are space heating and cooling plants which exploit the soil as a thermal source or sink, through the circulation of a heat carrier fluid in a closed pipe loop. Different pipe arrangements are available, among which the most common is the Borehole Heat Exchanger, a vertical pipe loop reaching depths of 50–200 m (Fig. 1). Below a depth of a few meters from the ground surface, the seasonal variation of the air temperature disappears due to the large thermal inertia of the soil. Therefore, if compared to the air, the soil is a warmer source for heating during winter and a cooler sink for cooling during summer, and higher system efficiencies can therefore be achieved compared to Air Source Heat Pumps.

GSHPs are rapidly spreading in Europe, China and USA, and have a great potential for energy, cost and CO_2 emission saving [1]. About 100,000 low-enthalpy geothermal plants are installed every year in Europe, mainly for new dwellings in Sweden, Germany and France [2,3]. According to Saner et al. [4], the use of GSHP in place of methane furnaces allows the CO_2 emissions to be reduced by up to 84%, depending on the sources used for the production of electricity. From the economic point of view, the geothermal heat pumps lead to a considerable reduction of the maintenance costs and, although their installation is more expensive than the other heating and cooling plants, the payback periods proved to be reasonable, i.e. less than 10 years [5–7].

Since the thermal exploitation of the soil induces a gradual temperature drift, an accurate heat transport modelling of soil and aquifer systems is essential for a correct design of GSHPs. Indeed, the efficiency of the heat pump is strongly influenced by the temperature of the heat carrier fluid, which in turns depends on the temperature of the surrounding soil. To estimate the thermal impact of BHEs and the working temperatures of the heat carrier fluid, different methods have been developed, which can be divided into analytical, semi-analytical and numerical.

The Kelvin infinite line source [8] and the infinite cylindrical source [9] are the simplest analytical methods for estimating the thermal disturbance induced by a BHE, since they rely on the assumption of a purely conductive and radial heat transport. Their main limitation is that of not accounting for the vertical thermal gradient and fluxes [10] and for the heterogeneity of the heat exchange over the length. Moreover, the advective and dispersive heat transport occurring in aquifer systems is also neglected. Nevertheless, these analytical solutions are still widely used for the interpretation of Thermal Response Tests [11], since they last for a short time (48 ÷ 72 h) and therefore the vertical heat transport can be neglected. The subsurface flow and the seasonal changes of groundwater levels can significantly alter the results of a TRT, as

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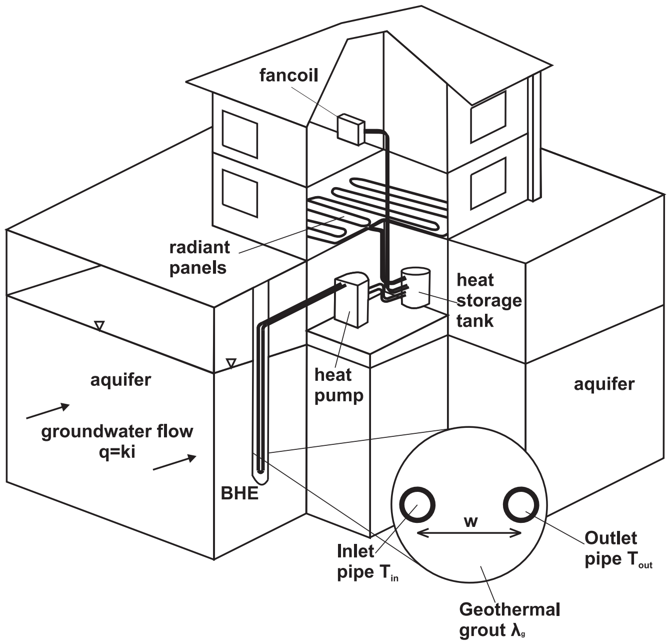

Fig. 1. Scheme of a Ground Source Heat Pump (GSHP): the Borehole Heat Exchanger (BHE) exchanges heat between the surrounding soil and the heat pump. A thermal storage tank reduces the frequency of start-up and stop of the heat pump. Radiant panels and fan coils are the most diffused heating terminals for GSHPs. If present, groundwater flow enhances the heat transport around the BHE, permitting to achieve better energy performances.

pointed out by Bozdağ et al. [12]. To overcome this problem, Wagner et al. [13] recently developed a method for the interpretation of TRTs in the presence of strong groundwater flow.

The semi-analytical method proposed by Eskilson [14] takes into account the finite length of the exchanger and different BHE field layouts, but the advection and the dispersion are neglected. This method is applied by two of the most popular BHE design software programmes, Earth Energy Design [15] and GLHEPRO [16].

Analytical models which take into account the beneficial effects of groundwater flow [17], of the finite length of the BHE [18], and both them together [19] have been developed in the last few years, and they could be used in the future for the dimensioning of BHE fields.

Recently, numerical modelling has often been applied to the design of BHE fields. The finite-difference modelling software MODFLOW can be used coupled with the solute transport package MT3D (or MT3DMS) and by applying the analogy between heat and solute transport [20,21], or with the specific heat transport package SEAWAT [22]. On the other hand, the finite element software FEFLOW includes a special package for the simulation of BHEs [23,24] which is particularly suitable for non conventional BHE field layouts and for taking into account the thermal advection and dispersion in aquifer systems.

The heat transport simulation of GSHPs permits the assessment of their performances, which are influenced by the properties of the exchanger and the thermo-hydrogeological parameters of the soil. According to Chiasson et al. [25], groundwater flow significantly enhances the performances of BHEs, and the Peclet number is a good indicator for whether advective transport needs to be taken into account or neglected. Wang et al. [26] have developed a method to estimate the velocity of groundwater movement measuring the temperature profiles in a BHE. Lee [27] has investigated the effect of vertical heterogeneities of the soil thermal conductivity, concluding that the adoption of depth-averaged thermal parameters is appropriate. Chung and Choi [28] have found that an increase of the fluid flow rate reduces the heat transfer rate per unit length. Delaleux et al. [29] have studied the increase of the thermal conductivity of grouts with the addition of graphite flakes, concluding that a noticeable heat transfer improvement is achieved by BHEs. Jun et al. [30] have evaluated the influence of running time, pipe spacing, grout conductivity, borehole depth, fluid flow rate, inlet fluid temperature and soil type on the heat transfer length and on the thermal resistance of borehole and soil. Michopoulos and Kyriakis [31] have found a non-linear relation between the BHE length and the heat pump consumption, which can be used for optimization processes in the dimensioning of large plants. The aforementioned studies deal with single or few parameters, but a thorough comparative analysis of all these factors together is still missing, and constitutes the objective of this work. The functioning of a single BHE was simulated for 30 years, using a benchmark cyclic thermal load and changing the operational parameters of the scenario. The resulting fluid temperatures at the end of the BHE were processed and used to estimate the COP of the heat pump and its annual energy consumption under different conditions. On the basis of the results it is possible to draw some practical conclusions on the margins of improvement of BHEs and on the proper choice of soil parameters for the simulations.

2. The modelling framework

The sensitivity analysis has been carried out on the design parameters of the BHE (geometrical setting, properties of the materials, flow rate etc.) and on the physical properties of the soil and the aquifer (thermal conductivity, groundwater flow velocity etc.), with the aim of evaluating their relative impact on the performances of a GSHP (i.e. evolution of the heat carrier fluid temperatures, energy consumption of the heat pump) in a realistic scenario and in long-term perspective.

The case study involves the simulations of the heating system of a house in the North of Italy, with a heated surface of 150 m^2 and a good thermal insulation. A heat pump connected to a BHE with a single U-pipe configuration is used only for heating. A cyclic thermal load (see Fig. 2) has been set, with a total heat abstraction of 12 MWh per year (80 kWh m^{-2} y^{-1}), which is equivalent to the energy produced by 1200 m^3 of methane or 1250 l of gasoil using an efficient boiler. The simulations last for 30 years, which is a sufficiently long time span to assess the long-term sustainability of the thermal exploitation of the soil.

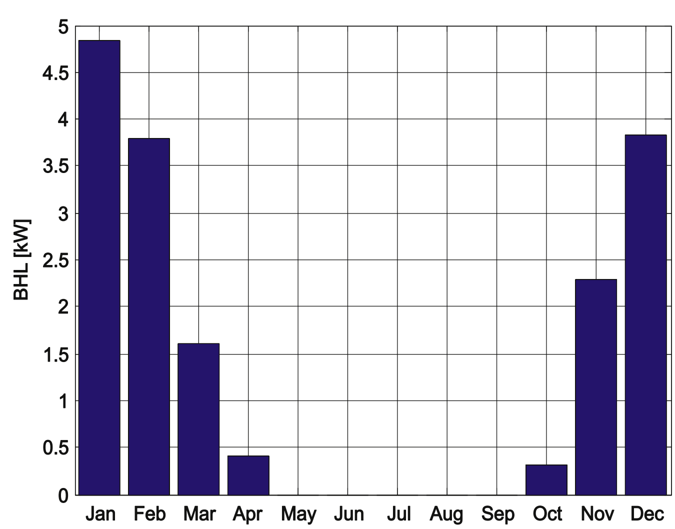

Fig. 2. Building Heat Load (BHL) adopted as a benchmark for the BHE in the simulations.