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Abstract. The correct design of the Borehole Heat Exchanger is crucial for the operation and the energy performance of a Ground Source Heat Pump. Most design methods and tools are based on the assumption that the ground is a solid medium where conduction is the only heat transfer mechanism. In turn in regions rich in groundwater the groundwater flow influence has to be assessed, by including the convection effects. In this paper a numerical model of a 100 m U-pipe in a saturated porous medium is presented. The model is created adopting MT3DMS coupled to MODFLOW. A Darcy flow is imposed across the medium. The typical operation of a Borehole Heat Exchanger operating both in winter and in summer is simulated for two years, under different groundwater velocities. The energy injected to and extracted from the ground is derived as a function of the Darcy velocity and compared with the purely conductive case. Temperature fields in the ground at key moments are shown and discussed. From both the energy and the aquifer temperature field points of view, the velocity ranges for respectively negligible and relevant influence of the groundwater flow are identified.

1. Introduction

Shallow geothermal energy is considered an environmental friendly alternative to traditional heating and cooling techniques. Either Ground Source Heat Pumps (GSHPs) or Groundwater Heat Pumps (GWHPs) can be used. In GSHP systems the heat pump is coupled to a closed loop buried into the ground, where a thermal-carrier fluid is circulated, extracting heat from the ground in winter and/or injecting heat into the ground in summer. The most widespread application consists of an arrangement of vertical boreholes (Borehole Heat Exchangers or BHEs), typically 100 m deep, where a single or a double U polyethylene pipe is inserted.

The correct design of the BHEs is crucial for the operation and the energy performance of the GSHP. Several design methods and tools are available, including thumb rules, simplified analytical models and more accurate dynamic simulation tools [1-4]. Moreover recently in Italy a design standard for GSHP and GWHP was published [5]. However most of the available methods are based on the assumption that the ground is a solid medium where conduction is the only heat transfer mechanism. In turn in some regions where GSHP are installed, such as the Padana Plain in Northern

Italy, the ground is extremely rich in groundwater. In such cases the groundwater flow influence on the energy performance of the BHEs has to be assessed, by including the convection effects.

The use of the Moving Line Source solution has recently been proposed to study the interaction between a BHE and a groundwater flow [6, 7]. In this approach the BHE is treated as a line heat source with a given constant heat rate, and then the thermal impact in the ground of the BHE operation is analyzed. However in reality the heat rate exchanged by the BHE is not assigned, since it is influenced by the temperature conditions that develop around it. Therefore an integrated approach, where the BHE operation produces a thermal perturbation into the ground and the temperature field in the ground influences the BHE energy performance, would be more useful.

On the experimental side, studies on BHEs under the influence of a groundwater flow are generally lacking and limited to tests in real conditions, such as in [8]. Yet controlled hydrogeological conditions are necessary in order to have a quantitative accurate assessment of the effects of the groundwater velocity on the energy performance of the BHE.

In the present paper the influence of the groundwater flow on the energy performance of a BHE is studied through a finite-difference numerical model implemented through the code MT3DMS [9] coupled to MODFLOW [10]. An integrated approach is followed, where the exchanged energy and the aquifer temperature field are solved together. An accurate validation of the model by comparing its predictions with the Moving Line Source ones has been carried out and may be found in [11]. The model is used to simulate a BHE operating in both seasons, namely extracting heat from the ground in winter and injecting it into the ground in summer. Two years of operation are considered, in order to understand the impact of the previous year operation on the next one. A broad range of groundwater velocities, well representative for a wide ensemble of hydrogeological systems, is considered. From the simulations the seasonal energy exchanged is derived and compared with the reference case of null groundwater velocity. Temperature conditions in the aquifer are analyzed at key moments. Finally the velocities ranges leading to respectively a negligible and a significant improvement of the BHE performance are clearly identified.

2. The simulation model

2.1. The case study

The case study refers to a typical BHE, consisting of a 100 m polyethylene U-pipe with an inner diameter of 4 cm and a pipe-to-pipe centers distance of 6 cm. The U-pipe is located into a 200 m saturated non-dispersive sandy aquifer, assumed homogeneous. For the sake of simplicity the borehole filling material is assumed to be equal to the surrounding soil. Milano, Northern Italy, conditions are assumed. Therefore the aquifer has an initial uniform temperature of 11.8°C. The BHE is simulated as if connected to a heat pump providing heating and cooling to a building. Five Darcy velocities are considered, namely 0 m/s, 10^{-7} m/s (0.86 cm/day), 10^{-6} m/s (8.6 cm/day), $5 \cdot 10^{-6}$ m/s (46.3 cm/day) and 10^{-5} m/s (86.0 cm/day). Porous medium thermal and hydrogeological properties are listed in table 1.

Table 1. Porous medium thermal and hydrogeological properties

Porosity	θ	0.35
Dispersivity	δ	0 m
Effective thermal conductivity	λ_m	2.3 W m^{-1} K^{-1}
Thermal capacity per unit volume	C_m	2.72 MJ m^{-3} K^{-1}
Hydraulic conductivities (5 cases)	k	$2 \cdot 10^{-4}$; $2 \cdot 10^{-5}$; $2 \cdot 10^{-4}$; 10^{-3}; $2 \cdot 10^{-3}$ m s^{-1}
Darcy velocities (5 cases)	v	0; 10^{-7}; 10^{-6}; 10^{-5} m s^{-1}

2.2. Model implementation

A MODFLOW/MT3DMS model of the U-pipe in a 3D domain has been implemented. MODFLOW is full 3D finite difference code for groundwater flow simulations developed by U.S. Geological Survey [9], while MT3DMS is a modular three-dimensional multispecies transport code, developed by Alabama University [10], for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. MT3DMS can accommodate very general spatial discretization schemes and is designed for use with any block-centered finite-difference flow model, such as MODFLOW.

Since only a rectangular grid can be used, the real circular geometry of the pipes has been turned into an equivalent square geometry, by imposing the conservation of the total thermal resistance between the thermal-carrier fluid into each pipe and the outer surface of the pipe [12]. Therefore, as shown in figure 1, a square section with 3.36 cm side has been used for the U-pipe. The grid cells have very different lengths, ranging from a minimum of 0.37 cm close to the BHE to a maximum of 10 m close to the domain boundaries. The domain length downstream depends on the velocity in order to allow the proper description of the temperature plumes developed by the BHE. Consequently the domain horizontal dimensions are 60 m x 90 m for the null velocity case, 60 m x 100 m for $v = 10^{-7}$ m/s, 60 m x 200 m for $v = 10^{-6}$ m/s and $v = 5.10^{-6}$ m/s, and finally 60 m x 340 m for $v = 10^{-5}$ m/s.
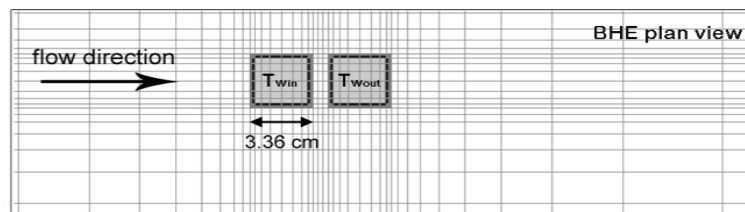
Figure 1. plan view of the numerical model grid: zoom of the zone around the BHE

The boundary conditions given to the model consist of an initial uniform temperature in the medium, a constant unperturbed temperature at the upstream boundary of the medium and a constant hydraulic gradient across the horizontal section. By varying the hydraulic gradient, the Darcy velocity of the groundwater is varied. For the BHE, constant mass flow rate $\dot{m}$ and inlet temperatures T_{wi} are given, as shown in table 2. While in real conditions the inlet fluid temperature may vary according to the GSHP control strategy and building heating/cooling load, a constant inlet fluid temperature approach, although simplified, allows to derive very general results, independent from the specific building and heat pump. As reported in table 2, a 6 months heat injection period during winter, a 3 months heat injection period during summer and two 1.5 months pauses or no operation periods between the two operation seasons can be identified.

**Table 2**. Operational parameters assigned to the BHE

	Interval	T_{wi} (°C)	$\dot{m}$ (kg/h)
heat extraction (winter)	15th Oct. – 15th Apr.	1	1000
pause	16th Apr-31st May;	-	-
heat injection (summer)	1st June – 31st Aug.	28	1000
pause	1st Sept – 14th Oct.	-	-

The model predictions have been compared with the Moving Line Source predictions, by running the BHE model in constant heat rate mode, as described more in detail in [11]. The difference between the numerical model and the analytical model temperature distributions in the aquifer was turned into a heat rate difference. It was found that the discrepancy ranges from 2 % for the null velocity case to -

9% for the highest velocity case, namely 10^{-5} m/s. Therefore the numerical model proved to be sufficiently accurate.

3. Simulation results

The energy extracted from and injected into ground by the BHE, respectively in winter and in summer, is shown in figure 2 as a function of the Darcy velocity. It may be noticed that more energy is exchanged during winter (extraction in the graph) than is exchanged during summer (injection in the graph), so that on a yearly basis the aquifer is used as a heat source. In order to observe a significant influence of the groundwater flow, a Darcy velocity equal to 10^{-7} m/s appears to be insufficient. In turn, for velocities equal to 10^{-6} m/s and larger, an important increase in the exchanged energy with respect to the null velocity case can clearly be observed. The increase is generally nonlinear. For null velocity and for 10^{-7} m/s a modest difference between the 1st and the 2nd year exchanged energies may be noticed, while for larger velocities the 2nd year data are almost coincident with the 1st year ones.
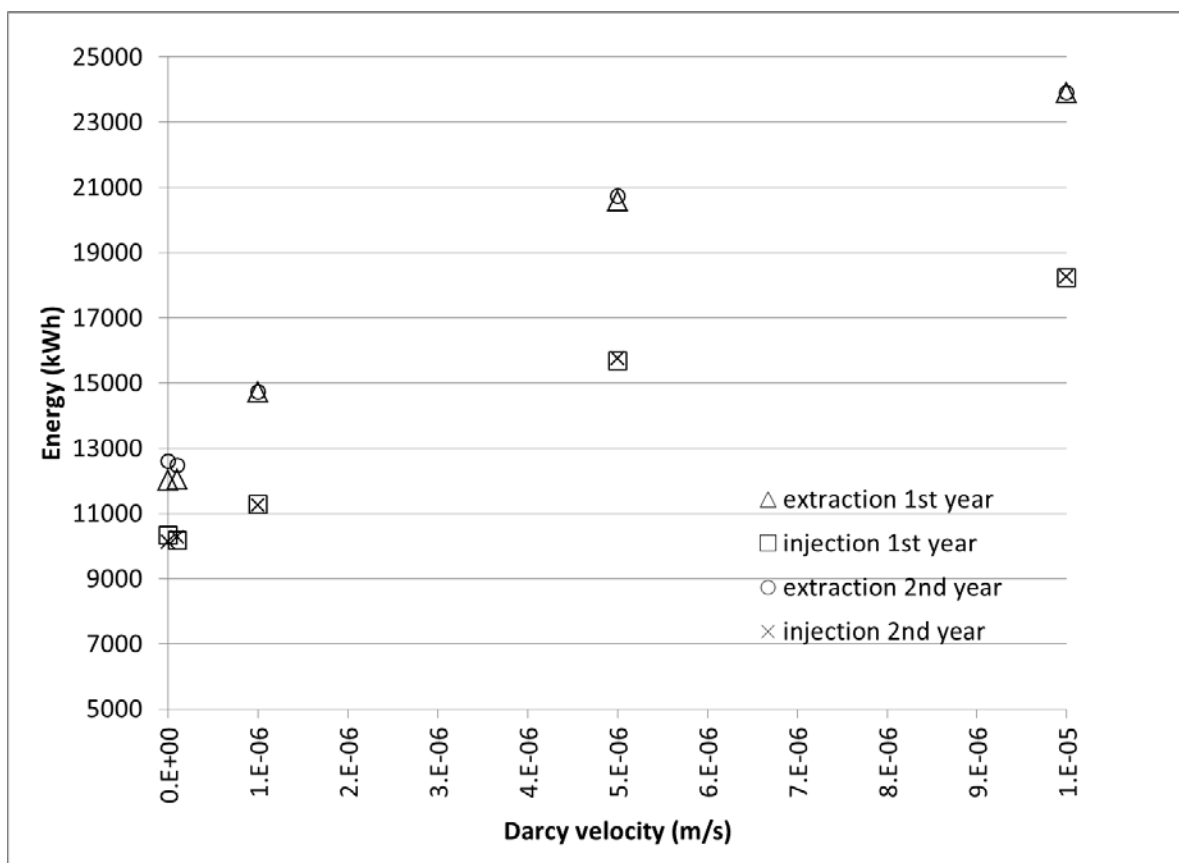

Figure 2. Energy extracted from or injected into the ground at 1st and 2nd year of operation versus Darcy velocity.

The increase in the extracted and injected energy with respect to the null velocity case can be plotted against the Darcy velocity, in a logarithmic scale, as in figure 3. For any given velocity, apart for $v = 10^{-7}$ m/s where negligible differences are found with respect to the null velocity case, considering the 1st year of operation, the extracted heat increases more than the injected heat. It is worth noting that in the 1st year of operation the simulation starts with the heat extraction period and, after a pause, the heat injection period starts. Therefore different temperature conditions are present in

the surrounding soil at the beginning of the extraction and injection periods, and this influences the results. In accordance with this remark, figure 3 shows that at the 2nd year of operation for each Darcy velocity the increases in the extracted and injected heat tend to approach.

Focusing then on the results related to the 2nd year of operation, as they appear less influenced by the initial temperature conditions, it may be stated that with respect to the null velocity case for $v = 10^{-7}$ m/s the energy variation is -1% in heat extraction and +2% in heat injection, for $v = 10^{-6}$ m/s it is +17% in heat extraction and +11% in heat injection, for $v = 5.10^{-6}$ m/s it is +65% in heat extraction and +56% in heat injection, and finally for $v = 10^{-5}$ m/s it is +90% in heat extraction and +80% in heat injection. Therefore it may be argued that for velocities larger than 10^{-6} m/s neglecting the convection effects leads to significant errors in the design of a BHE.
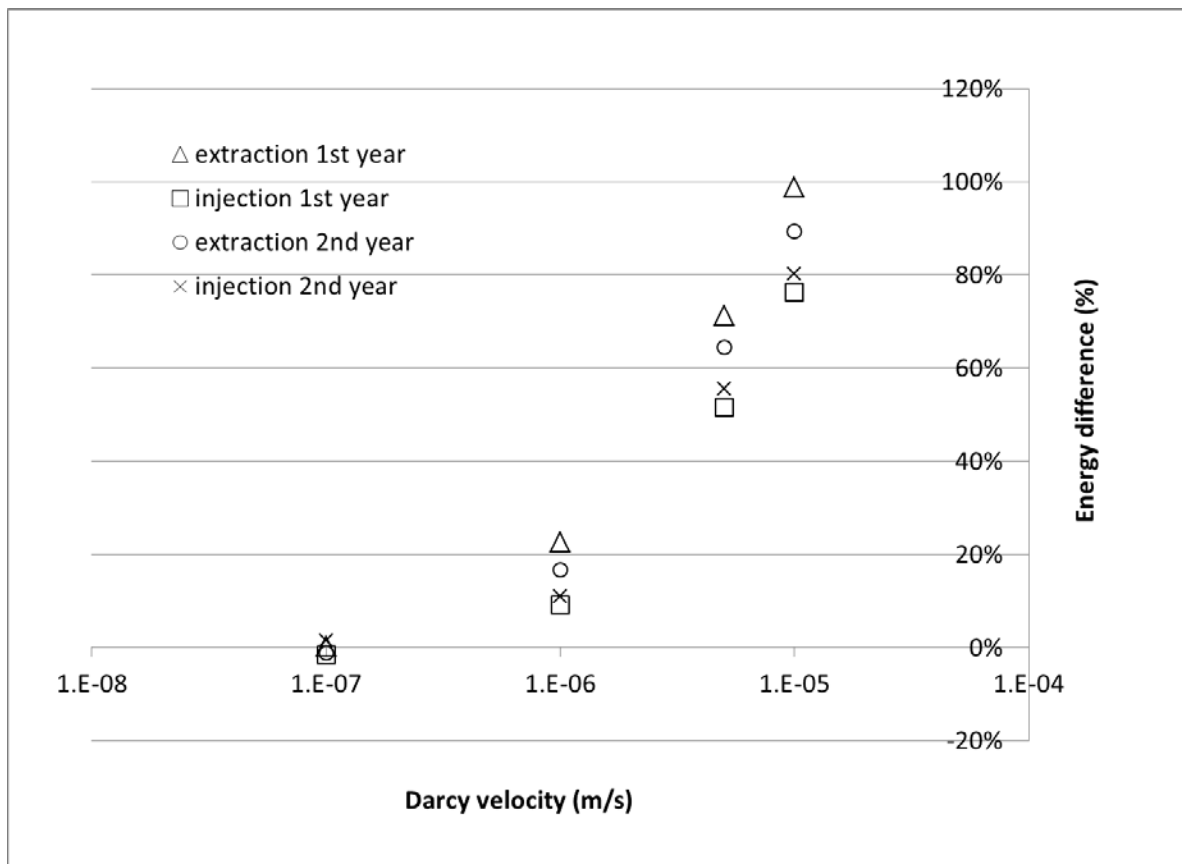

Figure 3. Difference in the exchanged energy with respect to the null velocity case, versus Darcy velocity, in the heat extraction and heat injection periods, at 1st and 2nd year of operation.
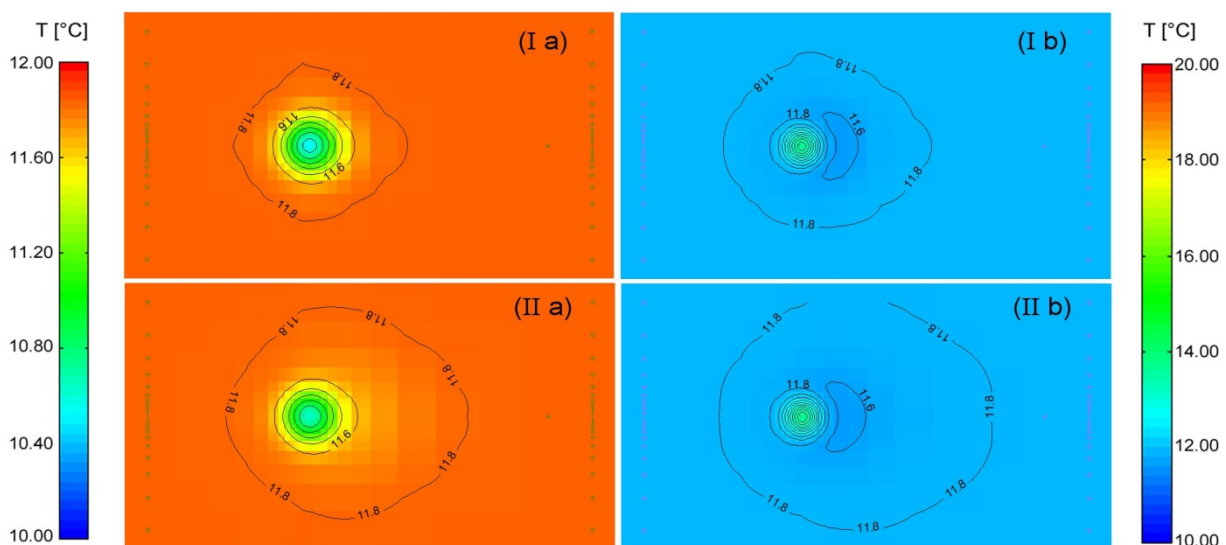
In figures 4, 5, 6 and 7 plan views of the temperature field in the aquifer are shown for respectively null velocity, $v = 10^{-7}$ m/s , $v = 10^{-6}$ m/s and $v = 10^{-5}$ m/s. The case $v = 5.10^{-6}$ m/s results in very similar conditions with respect to $v = 10^{-5}$ m/s and therefore for the sake of brevity is not shown. For every case, four moments are considered, namely the beginning of the heat injection period of the 1st year (Ia in figures), the beginning of the heat extraction period of the 2nd year (Ib in figures), the beginning of the heat injection period of the 2nd year (IIa in figures) and finally after two complete years (IIb in figures).

In general the cases of $v = 0$ (figure 4) and $v = 10^{-7}$ m/s (figure 5) are very similar: the temperature perturbation produced by the BHE operation in the previous season is centred on the BHE at the beginning of the next season, and therefore it has a positive influence on the energy performance in the next period. Moreover, for $v = 10^{-7}$ m/s the temperature contours are only slightly distorted in the

groundwater flow direction. With the latter velocity, a limited cold plume due to the previous heat extraction period is visible in Ib and IIb parts of figure 5.
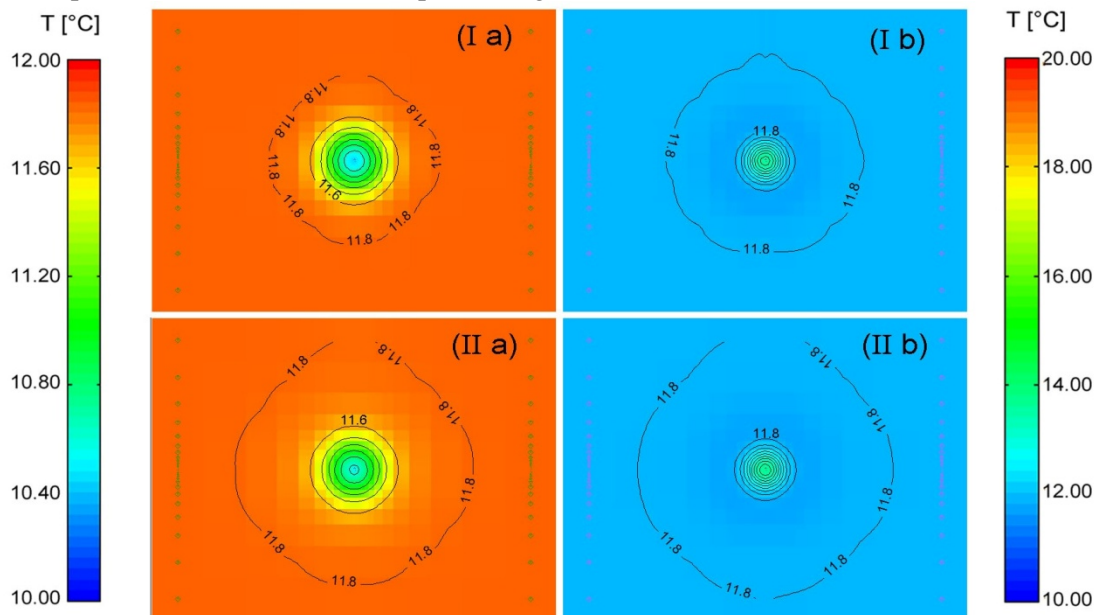
Figure 4: plan views of the temperature field in the aquifer for null velocity: Ia) beginning of heat injection 1st year; Ib) beginning of heat extraction 2nd year; IIa) beginning of heat injection 2nd year; IIb) after two years.
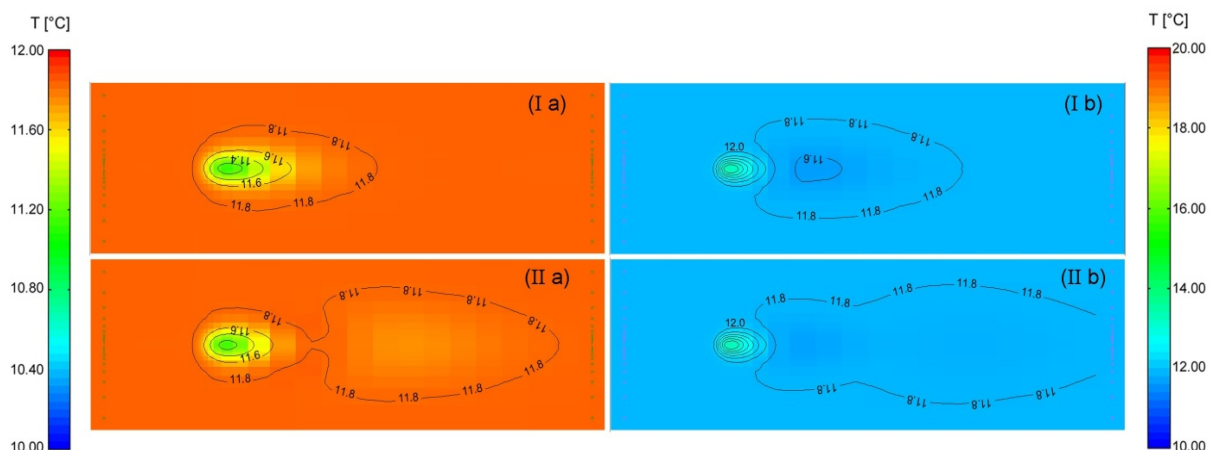

Figure 5: plan views of the temperature field in the aquifer for $v = 10^{-7}$ m/s Ia) beginning of heat injection 1st year; Ib) beginning of heat extraction 2nd year; IIa) beginning of heat injection 2nd year; IIb) after two years.

On the other side we find the $v = 10^{-5}$ m/s case (figures 7 and 8), where the high groundwater velocity brings away from the BHE most of the temperature perturbation due to the previous operating period. In these conditions, the benefits due to the use of the BHE in both seasons are less relevant. An intermediate behaviour is observed for $v = 10^{-6}$ m/s (figure 6): the effects of the previous season are still in the proximity of the BHE, although displaced downstream. In case $v = 10^{-6}$ m/s, apart from the beginning of the heat injection at the 1st year, two temperature plumes are generally visible, one due to the just finished operating period and another one due to the previous. Two temperature plumes are visible also for $v = 10^{-5}$ m/s, but only at the beginning of the heat injection periods. Since more energy

is extracted then injected (figure 2), the cold plume is expected to develop more than the warm one. Therefore for large groundwater velocity as $v = 10^{-5}$ m/s, the warm plume due to the previous heat injection is diluted, while the cold plume due to previous heat extraction is still visible. We can observe this specific situation better also in the vertical section view of this case (figure 8), where only one cold plume attends in Ia), while warm and cold plumes attend in Ib).

By comparing for each velocity the temperature fields Ia) and IIa) and, on the other side, Ib) and IIb), some considerations regarding the difference between the 1st and the 2nd year of operation may be derived. For $v = 0$ and $v = 10^{-7}$ m/s the temperature field at the 2nd year appear very similar to the 1st year, but the contour corresponding to the unperturbed temperature 11.8°C is displaced further from the BHE. For $v = 10^{-6}$ m/s, at the 2nd year the plume due to the just finished period is very similar to the 1st year, but the temperature plumes due to the past periods are more evident. Finally for $v=10^{-5}$ m/s no significant difference may be found between the 1st and the 2nd year temperature field, in agreement with the energy data (figure 2). Therefore the situation after two years is still evolving for $v = 0$, 10^{-7} and 10^{-6} m/s, while it can be considered steady for $v = 10^{-5}$ m/s.
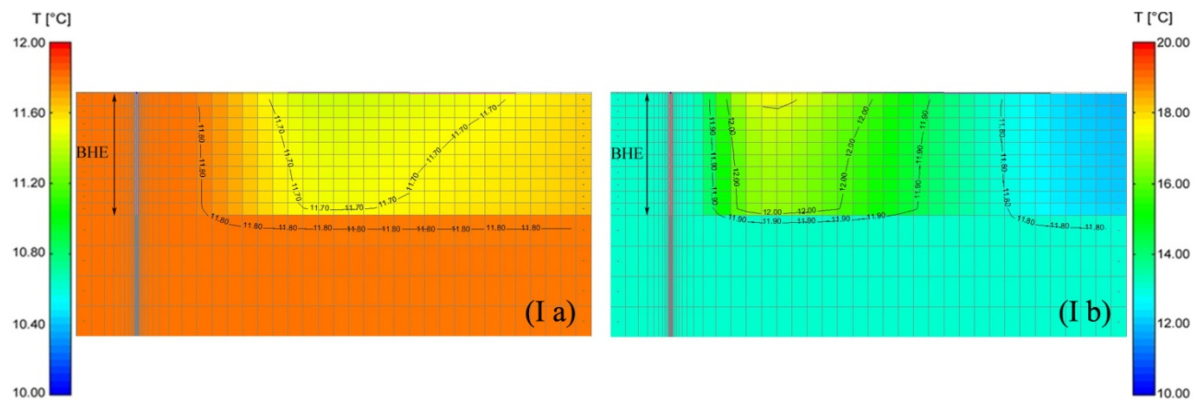

Figure 6: plan views of the temperature field in the aquifer for $v = 10^{-6}$ m/s: Ia) beginning of heat injection 1st year; Ib) beginning of heat extraction 2nd year; IIa) beginning of heat injection 2nd year; IIb) after two years.
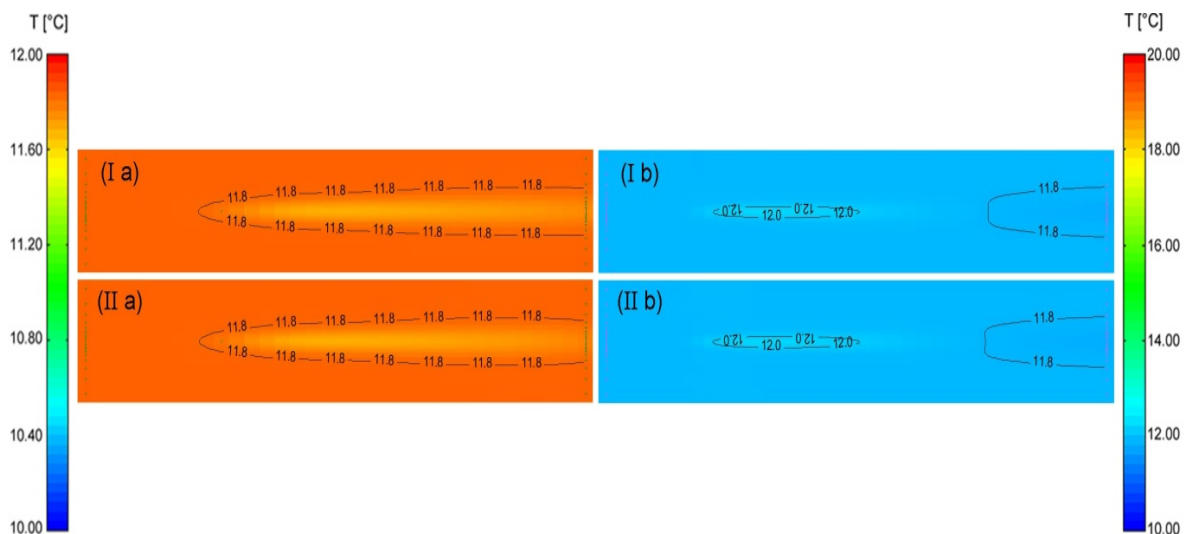
Figure 7: plan views of the temperature field in the aquifer for $v = 10^{-5}$ m/s: Ia) beginning of heat injection 1st year; Ib) beginning of heat extraction 2nd year; IIa) beginning of heat injection 2nd year; IIb) after two years.

Figure 8: vertical section views of the temperature field in the aquifer for v = 10^{-5} m/s: Ia) beginning of heat injection 1st year; Ib) beginning of heat extraction 2nd year.

4. Conclusions

By using a numerical model of a BHE composed of a single U-pipe 100 m long in a sandy aquifer under different groundwater velocities the impact of the groundwater flow on the BHE energy performance has been assessed. For velocity lower than 10^{-6} m/s the heat transfer in the aquifer is mainly due to conduction. In turn for velocity equal and larger than 10^{-6} m/s the injected and extracted energy increase with respect to the null velocity case, up to 80 and 90% more for 10^{-5} m/s. Therefore further efforts are necessary to include groundwater influence in the design methods for BHEs. The case study, referring to a BHE operating in both seasons with a yearly unbalance between energy extraction and injection for two years, highlights the importance of long term evaluations, that however are characterised by a high computational effort.

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