BOREHOLE HEAT EXCHANGERS: HOW FLOW VELOCITY AND DISPERSION INFLUENCE HEAT TRANSFER

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Introduction

Ground source heat pumps systems likely to use low enthalpy resources are gradually spreading, representing one of the most efficient and low environmental impact technologies for cooling and heating of buildings. Most common geothermal systems are made up of closed loop boreholes (Borehole Heat Exchangers or BHEs) buried into the ground, typically 100 m deep, where a thermal-carrier fluid is circulated into polyethylene U-pipes, extracting heat from the ground in winter and/or injecting heat into the ground in summer.

The energy performance of these systems depends on the heat transfer process between the BHEs and the ground. In many applications the ground can be considered as a purely conductive medium: in fact this hypothesis is at the base of many commercially available tools used to design BHEs, such as GHLEPRO or EED (Hellstrom 2001). Therefore some efforts have recently been carried out to include the effects of the presence of a groundwater flow into the BHEs modeling (Diao 2004). In this case the heat is transported not only by conduction but also by advection. Extending this problem could change the correct prediction of the energy performance of the BHEs and the investigation of the thermal impact, in terms of the temperature perturbation produced by the BHEs operation in surrounding aquifer. The aim of this work is the evaluation of these two aspects, varying the rate of groundwater flow velocity and dispersion coefficient using a numerical model realized through Modflow/MT3D (Angelotti 2014), already validated with respect to the Moving Line Source analytical solution (Molina-Giraldo 2011), demonstrating that both advection and dispersion play an important role in the heat transfer. Especially the dispersion coefficient is important because it depends on the ground heterogeneities, influencing the plume temperature in the ground.

Mathematical Modeling

A finite difference numerical model of a 100 m U-shape pipe in a saturated homogeneous sandy aquifer (thickness equal to 200 m) is created adopting Modflow coupled to MT3DMS (Fig.1).

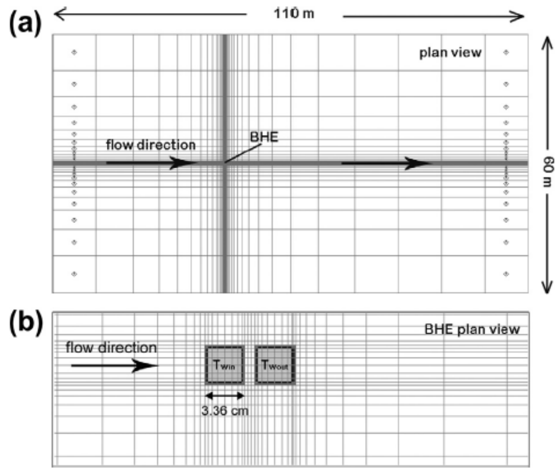

Fig. 1 – a) Plan view of the model and boundary conditions implemented in Modflow. b) Zoom on simulated BHE

This model is validated against the Moving Line Source analytical solution (Tab.1), both considering a null dispersion coefficient, resulting in a maximum discrepancy of 9%. A good agreement with the analytical solution was then found also in the case of a groundwater flow, although the relative error tends to increase with Darcy velocity (Angelotti et al. 2014). As already noticed by some authors some numerical dispersion effect may be expected in MT3DMS for advection-dominated situation: it will be present for high Darcy velocity values.

Darcy velocity (m/s)	q_{fit} (W/m)	Fit standard mean deviation (°C)	q_{fit} relative error (%)
0	40.7	0.024	1.7
10^{-7}	39.5	0.058	−1.2
10^{-6}	36.8	0.091	−8.0
10^{-5}	36.4	0.046	−9.0

Tab.1 – Comparison between the numerical model and the analytical solutions in constant heat rate operation

The boundary conditions given to the model consist of an initial uniform temperature in the medium, a constant unperturbed temperature at the physical boundaries of the medium and a constant hydraulic gradient across the horizontal section. By varying the hydraulic gradient and consequently the horizontal grid, the Darcy velocity of groundwater is varied (Tab.2). About the BHE, a given mass flow rate and inlet fluid temperature are given, according to the simulated period. Therefore the heat transfer rate of the BHE is not imposed, but depends on the temperature field in the aquifer.

Porosity, θ	0.35
Dispersivity, δ	0, 10 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 porous medium conductivities, k	2 x 10^{-4}; 2 x 10^{-5}; 2 x 10^{-3} m s^{-1}
Darcy velocities, v	0; 10^{-7}; 10^{-6}; 10^{-5} m s^{-1}

Tab.2 – Porous medium thermal and hydrogeological properties

Model simulations, considering heat extraction from the aquifer during wintertime and heat injection during summertime, regard the typical yearly operation of a BHE for a 2 years long period. For a given groundwater velocity, different dispersivity values (pointing out possible ground heterogeneities) are assigned to the cells representing the modeled sandy aquifer, in order to evaluate the effect of this parameter on the BHE performance and temperature distributions.
In particular, the impact of different groundwater velocities on the energy performance of a typical BHE in a sandy aquifer has been assessed and shown by Angelotti et al. (2013). In Fig. 2 a plan view of the temperature field in the ground at the end of the heat extraction period (winter) and at the end of the heat injection period (summer) is shown, for the different groundwater velocities. The average specific heat extraction rate during winter and heat injection rate during summer at different groundwater velocities are reported in Tab. 3 together with the percentage variation with respect to the purely conductive case (i.e. v = 0 m/s).

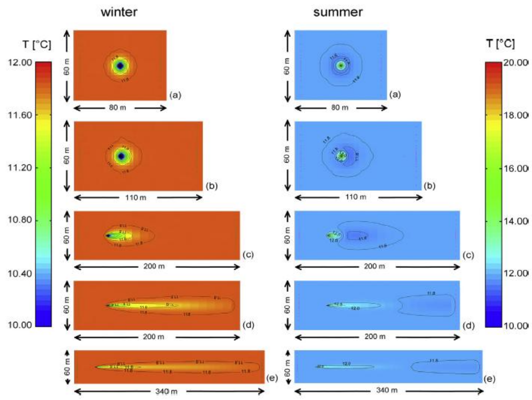

Fig. 2 – Plan view of the ground temperature at the end of the heat extraction period (left) and of the heat injection period (right) for 0 (a), 10^{-7} (b), 10^{-6} (c), $5x10^{-6}$ (d), 10^{-5} (e)

For v ≥ 10^{-6} m/s a significant increase (up to 80 % if v = 10^{-5} m/s) in the injected/extracted energy is found, so neglecting the advection effect due to groundwater may lead to significant errors in the design of a BHE.

Darcy velocity (m/s)	Pe	q Extracted (W/m)	q Injected (W/m)
0	0	27.3	45.3
10^{-7}	0.0085	27.1 (−1%)	46.1 (+2%)
10^{-6}	0.085	33.3 (+22%)	50.2 (+11%)
5×10^{-6}	0.43	48.0 (+76%)	73.0 (+61%)
10^{-5}	0.85	55.8 (+105%)	81.9 (+81%)

Tab.3 – Average specific heat rate (and percentage variation with respect to the purely conductive case) during heating and cooling operation periods for different Darcy velocities

Only recently in the Moving Line Source problem the dispersion coefficient has been taken in account. For this reason, some simulations with significant dispersivity values over the whole model domain are run in MT3D for the first year period for the case of 10^{-5} m/s groundwater velocity. Heat contours (Fig.3) show that, in a dispersive domain, the plume can spread around the BHE, producing thus a perturbation of temperatures in the transverse direction.

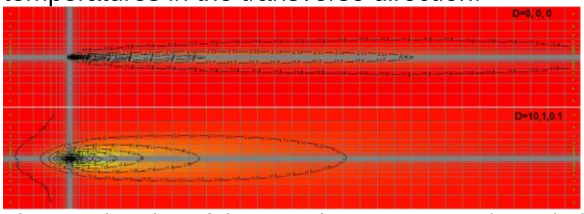

Fig. 3 – Plan view of the ground temperature at the end of the heat extraction period for 10^{-5} m/s and null dispersivity case compared with 10^{-5} m/s and maximum dispersivity value case

In particular, the 10 m longitudinal dispersivity configuration is deeper examined because of its relevant weight in literature values. When 10^{-5}m/s groundwater flow is present, total developed energy results to be higher than when dispersion is not set: the percentage difference is 97.8% for the heating period, whereas it is 94.7% for the cooling period (Fig.2).

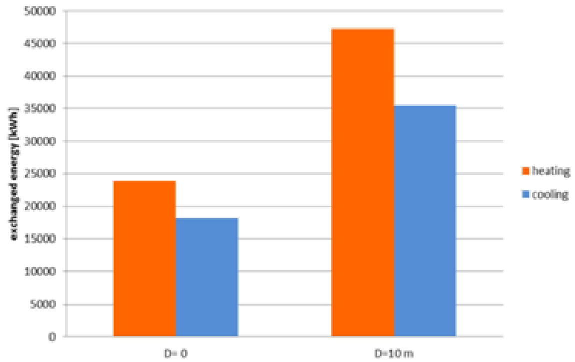

Fig. 4 – Exchanged energy in the case of groundwater flow V = 10^{-5}m/s, with null dispersivity and 10 m dispersivity

Results regard also temperature distribution into the entire model domain. In fact three observation wells are set transverse to the downstream flux in order to observe difference between the cases with and without dispersion; hence a series of 41 monitoring wells is set along the downstream flux in order to look at the temperature variation with time (Fig.3).

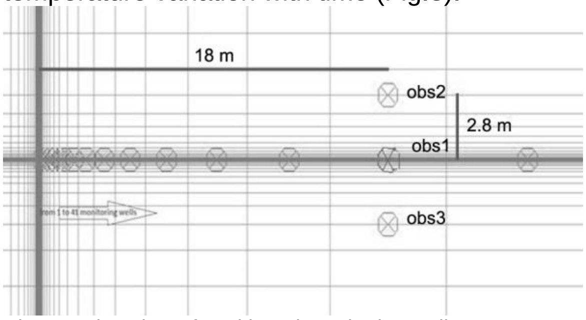

Fig. 5 – Plan view of positioned monitoring wells

Results taken from the three monitoring wells show that observed temperature values, where dispersion is applied, are smaller for OBS1 than in the case without dispersion. Sensors far from the flow line register a lateral spreading of the heat if dispersion is applied, equal to that registered in OBS1. The 41 observation wells downstream of the BHE (Fig. 4) show that, where dispersion is present, the BHE's disturbance can dissolve also laterally: it disappears almost 92 meters before than in the case without dispersion.

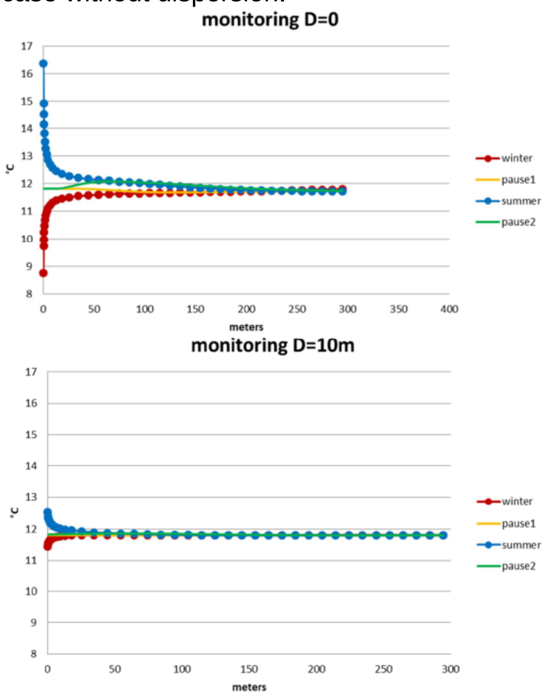

Fig. 6 – Temperature profile in the ground (with or without dispersion cases)

From the Fig. 4, it is possible to observe a bigger disturbance when the dispersivity is not set beacuase of the lateral spreading due to the introduction of maximum dispersivity value; this will also influence the energy performance of the BHE.

Conclusions

These results demonstrate that, even if heat transfer simulations generally neglects dispersion, the effect of this phenomenon is really important and heavily influences the results, especially in terms of exchanged energy. Further efforts are then necessary in order to better define the sensitivity of a numerical model to dispersivity parameter and hence to highlight the most suitable value to correctly estimate the energy transport in the presence of groundwater flow. In fact it is possible to notice that there are many disagreements from a deep bibliographic research: for a case of Peclet number, depending on the Darcy velocity and consequently on the ground heterogeneities, equal to a range between 0.1 and 1, the good range of longitudinal dispersivity is equal to the range between 0.03 and 1 m. But considering also a dispersivity value equal to 1 m, from the simulations, it can be observed that it leads to an high energy increase, equal to 49 %. So, the ground heterogeneities, with different dispersivity values, could influence the heat transfer for a not negligible quantity; only a deeper study in order to create a new correlation will lead to find out the correct value to assign to different ground layers of the model.

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