



# Politecnico di Torino

## Porto Institutional Repository

[Article] Efficiency of closed loop geothermal heat pumps: A sensitivity analysis

*Original Citation:*

Alessandro Casasso;Rajandrea Sethi (2014). *Efficiency of closed loop geothermal heat pumps: A sensitivity analysis*. In: [RENEWABLE ENERGY](#), vol. 62, pp. 737-746. - ISSN 0960-1481

*Availability:*

This version is available at : <http://porto.polito.it/2514912/> since: September 2013

*Publisher:*

Elsevier

*Published version:*

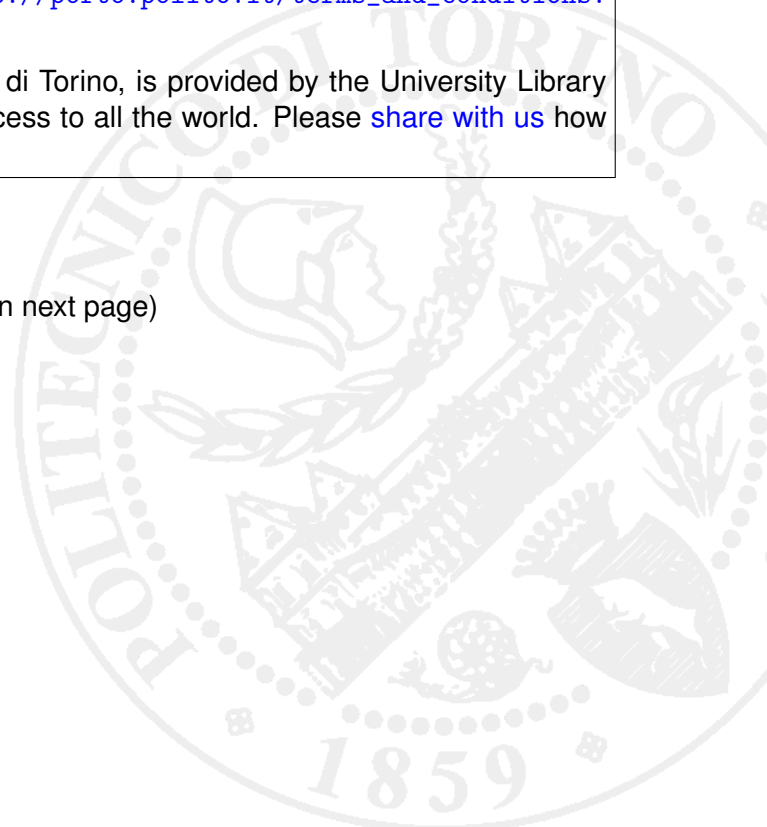
DOI:[10.1016/j.renene.2013.08.019](https://doi.org/10.1016/j.renene.2013.08.019)

*Terms of use:*

This article is made available under terms and conditions applicable to Open Access Policy Article ("Public - All rights reserved") , as described at [http://porto.polito.it/terms\\_and\\_conditions.html](http://porto.polito.it/terms_and_conditions.html)

Porto, the institutional repository of the Politecnico di Torino, is provided by the University Library and the IT-Services. The aim is to enable open access to all the world. Please [share with us](#) how this access benefits you. Your story matters.

(Article begins on next page)



1

2

3 Efficiency of closed loop geothermal heat pumps: a  
4 sensitivity analysis

5

6 *Alessandro Casasso, Rajandrea Sethi\**

7 DIATI – Dipartimento di Ingegneria dell’Ambiente, del Territorio e delle Infrastrutture

8 Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy

9 \*Corresponding author (email: [rajandrea.sethi@polito.it](mailto:rajandrea.sethi@polito.it))

10 **Abstract**

11 Geothermal heat pumps are becoming more and more popular as the price of fossil fuels is  
12 increasing and a strong reduction of anthropogenic CO<sub>2</sub> emissions is needed. The energy  
13 performances of these plants are closely related to the thermal and hydrogeological properties of the  
14 soil, but a proper design and installation also plays a crucial role. A set of flow and heat transport  
15 simulations has been run to evaluate the impact of different parameters on the operation of a GHSP.  
16 It is demonstrated that the BHE length is the most influential factor, that the heat carrier fluid also  
17 plays a fundamental role, and that further improvements can be obtained by using pipe spacers and  
18 highly conductive grouts. On the other hand, if the physical properties of the soil are not surveyed  
19 properly, they represent a strong factor of uncertainty when modelling the operation of these plants.  
20 The thermal conductivity of the soil has a prevailing importance and should be determined with in-  
21 situ tests (TRT), rather than assigning values from literature. When groundwater flow is present, the  
22 advection should also be considered, due to its positive effect on the performances of BHEs; by  
23 contrast, as little is currently known about thermal dispersion, relying on this transport mechanism  
24 can lead to an excessively optimistic design.

25

26 **Keywords:**

27 Low-enthalpy geothermal energy, Borehole Heat Exchanger, Ground Source Heat Pump, Heat  
28 transport, Groundwater

## 29 **1. Introduction**

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

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

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

52 The Kelvin infinite line source [8] and the infinite cylindrical source [9] are the simplest analytical  
53 methods for estimating the thermal disturbance induced by a BHE, since they rely on the

54 assumption of a purely conductive and radial heat transport. Their main limitation is that of not  
55 accounting for the vertical thermal gradient and fluxes [10] and for the heterogeneity of the heat  
56 exchange over the length. Moreover, the advective and dispersive heat transport occurring in  
57 aquifer systems is also neglected. Nevertheless, these analytical solutions are still widely used for  
58 the interpretation of Thermal Response Tests [11], since they last for a short time (48÷72 h) and  
59 therefore the vertical heat transport can be neglected. The subsurface flow and the seasonal changes  
60 of groundwater levels can significantly alter the results of a TRT, as pointed out by Bozdağ et al.  
61 [12]. To overcome this problem, Wagner et al. [13] recently developed a method for the  
62 interpretation of TRTs in the presence of strong groundwater flow.

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

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

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

77

78 The heat transport simulation of GSHPs permits the assessment of their performances, which are  
79 influenced by the properties of the exchanger and the thermo-hydrogeological parameters of the

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

101

## 102 **2. The modelling framework**

103 The sensitivity analysis has been carried out on the design parameters of the BHE (geometrical  
104 setting, properties of the materials, flow rate etc.) and on the physical properties of the soil and the

105 aquifer (thermal conductivity, groundwater flow velocity etc.), with the aim of evaluating their  
 106 relative impact on the performances of a GSHP (i.e. evolution of the heat carrier fluid temperatures,  
 107 energy consumption of the heat pump) in a realistic scenario and in long-term perspective.

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

115

116 The simulation of the heat exchange of the BHE with the soil and the aquifer system has been  
 117 performed with FEFLOW 6.0, a 3D finite element flow and solute/heat transport model [32, 33]  
 118 that includes specific tools for the simulation of Borehole Heat Exchangers [23, 24]. The software  
 119 solves the coupled equations of flow and heat transport in the soil, and the BHE is modelled as an  
 120 internal boundary condition of the 4<sup>th</sup> kind (thermal well).

121 The heat transport occurs by conduction (driven by thermal gradients), advection (due to the  
 122 groundwater flow) and dispersion (due to deviations from the average advective velocity), which  
 123 are described by the heat conservation equation in the porous medium:

$$124 \quad \frac{\partial}{\partial t} [(\varepsilon \rho_w c_w + (1 - \varepsilon) \rho_s c_s) T] + \frac{\partial}{\partial x_i} (\rho_w c_w q_i T) + \frac{\partial}{\partial x_i} \left[ (\lambda_{ij}^{cond} + \lambda_{ij}^{disp}) \frac{\partial T}{\partial x_j} \right] = H$$

125

1

126 where  $\varepsilon$  is the porosity,  $\rho_s$  and  $\rho_w$  are the density of the solid and liquid phase,  $c_s$  and  $c_w$  are the  
 127 specific heat of the solid and liquid phase,  $T$  is the temperature (which has been assumed equal for

128 both the phases),  $x_i$  is the  $i$ -th axis (i.e.  $x_1 \equiv x, x_2 \equiv y, x_3 \equiv z$ ) and  $q_i$  is the  $i$ -th component of the  
 129 Darcy velocity (i.e. relative to the  $i$ -th axis), and  $H$  is the heat source or sink (the BHE in this case),  
 130 The first term of Eq.1 describes the soil temperature variation with time, involving the porosity  $\varepsilon$   
 131 and the heat capacity of the solid matrix  $(\rho c)_s$  and of water  $(\rho c)_w$ .

132 The second term describes the advection, which depends on the Darcy velocity  $q$ .

133 The conduction and dispersion are respectively described by the tensors of the thermal conductivity  
 134  $\lambda_{ij}^{cond}$  and  $\lambda_{ij}^{disp}$  (third term of Eq.1):

$$135 \quad \lambda_{ij}^{cond} = \begin{cases} (1-\varepsilon)\lambda_s + \varepsilon\lambda_w & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases}$$

136 2

$$137 \quad \lambda_{ij}^{disp} = \rho_w c_w \left[ \alpha_T q \delta_{ij} + (\alpha_L - \alpha_T) \frac{q_i q_j}{q} \right]$$

138 3

139 where  $\lambda_s$  and  $\lambda_w$  are the thermal conductivities of the solid matrix and of groundwater,  $\alpha_L$  and  $\alpha_T$   
 140 are the longitudinal and the transverse dispersivity (with respect to the direction of groundwater  
 141 flow) and  $q$  is the modulus of the Darcy velocity.

142  
 143 The temperature of the soil at the borehole wall, calculated by the 3D finite-element modelling  
 144 code, is used to solve the balance of the thermal fluxes inside the BHE according to the Thermal  
 145 Resistance and Capacity Model (TRCM) of Bauer et al. [34]. The BHE is decomposed into  
 146 different elements (inlet and outlet pipe, grout zones, borehole wall), which are represented by the  
 147 nodes of the circuit, connected by thermal resistances, which depend on the geometrical settings and  
 148 the physical properties of the materials. Thermal energy conservation equations are solved, which  
 149 describe the balance of thermal fluxes between the components of the BHE, and the temperature of  
 150 each component is calculated [23]. Since no abrupt changes occur in the thermal load, the analytical



151 method based on Eskilson and Claesson's solution [35], which considers a stationary equilibrium  
152 between the soil and the BHE, has been used in the simulations in order to reduce the computational  
153 time if compared to the Al Khoury et al.'s [36, 37] transient model.

154

155 A very large square mesh domain, with a side of 1000 m and a thickness of 150m, has been used to  
156 avoid boundary effects on the computed BHE fluid temperatures. The 31 flat slices are equally  
157 spaced (5m of distance) and the total number of nodes is 15531. The mesh density has been set  
158 using the "BHE node rule" [38], positioning the nodes around the BHE on the vertexes of a regular  
159 hexagon, with a radius of 0.46 m (6.13 times the borehole radius), since Diersch et al. [24] proved  
160 that this mesh density achieves a higher precision in the results, even when compared with finer  
161 meshes.

162

163 The thermal balance of the soil around the BHE has been reproduced choosing appropriate  
164 boundary conditions. The temperature of the soil is almost constant through the year and, at an  
165 infinite distance from the BHE, it is not affected by the thermal exchange. Constant temperature  
166 values (1<sup>st</sup> kind heat transport b.c.) have therefore been imposed at the lateral boundaries of the  
167 domain, at least 500 m far away from the BHE. The heat flux coming from the deep layers of the  
168 Earth (geothermal flux), which has a mean value of  $0.065 \text{ Wm}^{-2}$  on the continental crust [39],  
169 induces a temperature vertical gradient with typical values around  $0.03 \text{ }^\circ\text{C/m}$ . According to these  
170 considerations, a temperature of  $12^\circ\text{C}$  has been set at the border or the first slice (which is a typical  
171 value of the annual mean air temperature in Northern Italy), incrementing the temperatures of  
172  $0.15^\circ\text{C}$  every 5m of depth ( $0.03 \text{ }^\circ\text{C/m}$ ). The initial conditions have been set consistently with the  
173 boundary conditions, with a homogeneous distribution of the soil temperature at each slice.

174

175 An unconfined aquifer, with a water table depth of 20m in the centre of the mesh (where the BHE is  
176 positioned), has been modelled assigning constant hydraulic head (1<sup>st</sup> kind) flow boundary

177 conditions along the mesh borders. A homogeneous and isotropic hydraulic conductivity  
178 ( $K = 10^{-4} \text{ m/s}$ ) has been assigned, and different hydraulic gradients, ranging between 1‰ and 20‰,  
179 have been imposed to change the groundwater flow velocity. Also different values of the saturated  
180 thickness of the phreatic aquifer have been adopted, ranging from 10m to 50m in the middle of the  
181 mesh, where the BHE is located.

182

183 A large set of simulations has been run in order to ascertain the influence of design parameters  
184 (length, pipe spacing, pipe diameter, heat carrier fluid and its flow rate, grout thermal conductivity),  
185 soil thermal (thermal conductivity of the solid matrix, thermal dispersivity) and hydrogeological  
186 properties (groundwater flow velocity, aquifer saturated thickness) on the performances of a BHE  
187 over a long operation period (30 years).

188 The adopted values of the BHE length range between 50 and 100 m, using a default value of 75 m.  
189 The borehole diameter is 0.15 m for all the simulations, and the HDPE pipes have an external  
190 diameter of 32mm and a wall thickness of 2.9 mm. The pipe spacing depends on the kind of spacers  
191 and from the pipe curvature given by the coil shape, which they keep even when they are unrolled:  
192 it varies therefore with depth and could not be known precisely. Different values have therefore  
193 been adopted, ranging from 35 to 117 mm between the pipe centres.

194 A set of simulation has been run to assess the performances of the most commonly adopted heat  
195 carrier fluids, and also different flow rates have been assigned ( $0.1 \div 0.7 \text{ ls}^{-1}$  with propylene glycol at  
196 25% weight concentration). The default fluid is calcium chloride at 20% weight, which proved to be  
197 the most performing one.

198 The thermal conductivity of the BHE filling can vary in a wide range, and values between 1 and 5  
199  $\text{Wm}^{-1}\text{K}^{-1}$  have therefore been adopted, while its thermal capacity does not experience great  
200 variations, and hence a unique value ( $2 \text{ MJm}^{-3}\text{K}^{-1}$ ) has been used for all the simulations.

201 Some of the thermal and hydrogeological parameters of the soil have been kept constant for all the  
202 simulations, like the thermal properties of water ( $\lambda_w = 0.6 \text{ Wm}^{-1}\text{K}^{-1}$  and  $(\rho c)_w = 4.2 \text{ MJm}^{-3}$ ), the  
203 thermal capacity of the soil solid phase ( $(\rho c)_s = 2.52 \text{ MJm}^{-3}$ ) and both the total and the effective  
204 porosity (respectively  $\varepsilon = 0.3$  and  $n_e = 0.2$ ), while the others have been changed to assess their  
205 influence on the performances of the geothermal systems. As the heat transport occurs by  
206 conduction, advection and dispersion, large ranges of the solid phase thermal conductivity ( $1 \div 3$   
207  $\text{Wm}^{-1}\text{K}^{-1}$ ), the Darcy velocity of groundwater ( $0 \div 17.32 \text{ md}^{-1}$ ) flow and the longitudinal/transverse  
208 thermal dispersivity ( $0 \div 5 \text{ m}$ ) have therefore been investigated.

209

210 The time series of the borehole fluid temperatures (Fig.3A) have been processed, calculating a  
211 cumulative temperature distribution (Fig.3B) during the heating seasons over the whole simulation  
212 period (30 years), which serves as a synthetic indicator to compare the different cases and to draw  
213 conclusions on the energetic performance of the system. Observing the fluid temperature duration  
214 curves in Fig.4 and Fig.5, one can understand how long will the heat pump work in a certain source  
215 temperature range. For example, Fig.4A shows that, for a 75m long BHE, the mean fluid  
216 temperature is below  $0^\circ\text{C}$  for the 19.51% of the heating period (say, 41.37 days a year), while this  
217 percentage rises up to 50.86% for a 50m long borehole (107.83 days a year).

218

219 The Coefficient of Performance (COP), which is the ratio between the heating power delivered to  
220 the building and the electrical power absorbed by the heat pump, depends on the temperatures of the  
221 heat source (the BHE fluid) and of the heat sink (the heating terminals of the building). The  
222 relationship of COP from fluid temperatures has been approximated with a linear formula:

223

$$COP = a + b \cdot T_f$$

224

4

225 where  $T_f$  is the average fluid temperature between the inlet and outlet pipes of the BHE, while  $a$   
226 and  $b$  depend on the heating terminal. For this study, we have set  $a = 4$  and  $b = 0.1 K^{-1}$ , which are  
227 typical values for radiant panels at 35°C.

228 The estimated COP values at each time step ( $COP_i$ ) have been used to calculate the energy  
229 consumption of the heat pump:

$$230 \quad HPC = \sum_{i=1}^n \frac{BHL_i}{COP_i} \cdot \Delta t$$

231 5

232 where  $BHL_i$  is the value of the BHE heat load at the  $i$ -th time step and  $\Delta t$  is the length of the  
233 constant time step (1 day). The electricity consumed by the heat pump gradually increases, as the  
234 soil and the BHE fluid is gradually cooling: the average value of yearly electricity consumption in  
235 the operation period (30 years) has been therefore used to evaluate the energy performance of the  
236 different BHE settings (Fig.6).

237

### 238 **3. Results and discussion**

239 The results of the long-term BHE simulations have been processed and compared in order to  
240 understand which is the relative importance of each parameter on the performances of the system  
241 and which is the margin of error due to the uncertainty in its determination, in particular for soil  
242 properties. Statistics about the calculated fluid temperatures (average, RMSE), the Seasonal  
243 Performance Factor (SPF) and the heat pump consumption for each simulation are summarized in  
244 the tables reported in the supporting information.

245

246 The length of the Borehole Heat Exchanger(s) plays a crucial role in the design process, because it  
247 accounts for about half of the total installation cost in single-house plants (see Blum et al. [40]).

248 Varying the BHE length between 50 and 100m, we observe a strong variation of the cumulate

249 distributions of the average fluid temperatures (Fig.4A) and of the value of the minimum fluid  
250 temperature, which is a critical parameter in the operation of a GSHP. The effect of the length  
251 increase is non-linear and diminishes for larger BHE sizes: for example, incrementing the length by  
252 between 50 and 75 m results in an increment of 2.80°C in the mean temperature, and of 1.58°C  
253 when the increment is from 75 m to 100 m; the minimum inlet temperatures are incremented  
254 respectively by 4.15°C and 1.92°C in the same ranges. The differences in the distributions of fluid  
255 temperatures also have a noticeable impact on the energy expense of the heat pump, as shown in  
256 Fig.6A. As for the cumulate distributions of the fluid temperatures, the effect of additional BHE  
257 length is reduced as the borehole depth increases (- 5.88% between 50 m and 75 m, -2.77% between  
258 75 m and 100 m).

259

260 The improvement of the energy performance with longer exchangers is compensated by a rise in the  
261 installation costs, which are the main drawback of geothermal heat pumps. In the dimensioning of  
262 BHE fields, usually a minimum and/or maximum fluid temperature constraint is imposed, and the  
263 minimum required borehole size is calculated [15, 16]. This approach minimizes the installation  
264 costs, but the maintenance costs are not taken into account, and the extra-cost due to a low COP can  
265 overcome the initial saving incurred with a smaller drilled depth. Starting from the results of the  
266 sensitivity analysis on the length of the BHE, we have considered the typical electricity and BHE  
267 installation costs of Italy (see Tab. 2) and calculated the total costs of installation and maintenance  
268 of the GSHP over a lifetime of 30 years. Since the unit cost of electricity is likely to increase over  
269 the next few decades, the analysis took into account different increase rates, in the range  
270 between 0% and 5%. In Fig.7, the ratio between the lifetime cost for each BHE length and the most  
271 expensive solution for each scenario of energy cost increase is shown, to identify the optimal size  
272 for each case. We observe that higher increments of the unit cost of electricity enlarge the optimal  
273 range of the BHE length, and shift it towards larger values; although it is not shown in the graph, a  
274 decrease of the drilling cost also achieves the same effect. GSHPs need larger investments

275 compared to the other heating and cooling plants, and loan rates have been also considered when  
276 evaluating the optimal length. Nevertheless, the influence of the interest rate on the total cost of the  
277 plant over its lifetime proved to be negligible, compared to the cost of electricity and its increasing  
278 trend.

279 A default length of 75 m was used in the other simulations, since it proved to be a reasonable choice  
280 for most of the scenarios depicted in Fig.7. The considerations on BHE length that we have made  
281 here concern only the lifetime cost of the plant, without taking into account the effects of very low  
282 fluid temperatures. For example, if a GSHP operates at temperatures below 0°C for a sufficiently  
283 long time, ground freezing can occur, and the borehole grouting can be fractured by freezing-  
284 thawing cycles. In addition, the viscosity of the heat carrier fluid increases as the temperature  
285 decreases, therefore the energy consumption of the circulation pump also increases. A low  
286 temperature threshold should therefore be established, which excludes some of the BHE lengths  
287 considered in this analysis: for example, setting a minimum inlet temperature of -3°C excludes  
288 lengths below 70 m.

289  
290 Although the borehole depth exerts the greatest influence on the economic balance of a BHE  
291 installation, there are also other factors which have to be taken into account. In the U-pipe BHEs  
292 (both single and double), which are the most diffused kind of installation, the pipes should be put as  
293 far as possible, to reduce both the thermal resistance of the exchanger and the heat exchange  
294 between the inlet and the outlet pipes (thermal short-circuit), which impair the performances of  
295 these systems. The thermal conductivity of the borehole filling plays an important role: a higher  
296 value reduces the borehole resistivity, but also the grout-to-grout resistance, which prevents the  
297 thermal short-circuit. Both these factors have been taken into account in the simulations, according  
298 to the borehole resistance model of Bauer et al. [34]. The distance between the pipe centres has  
299 been varied between 35 mm (i.e. 3 mm between the pipe walls) and 117 mm (i.e. 0.5 mm between  
300 the pipe wall and the borehole wall), and the thermal conductivity of the grout has been varied

301 between  $1 \text{ Wm}^{-1}\text{K}^{-1}$  (i.e. a poor grout) and  $5 \text{ Wm}^{-1}\text{K}^{-1}$  (i.e. special grouts with highly conductive  
302 graphite flakes [29]). Usually, the grouts employed for BHEs have a thermal conductivity of  $2\div 2.5$   
303  $\text{Wm}^{-1}\text{K}^{-1}$ , but this value can dramatically decrease due to an incorrect mixing, an excessive water  
304 content or an insufficient concentration of thermal additives [41]. Observing the cumulate  
305 distributions of the fluid temperatures (Fig.4B-C), we understand that the influence of the thermal  
306 conductivity of the grout is very large when the pipe spacing is reduced; on the other hand, a grout  
307 with a high thermal conductivity can compensate the negative effects of an insufficient pipe spacing  
308 on both the minimum fluid temperatures and the energy consumption of the system (Fig.6B). For  
309 example, if a common geothermal grout is used ( $\lambda_g = 2 \text{ Wm}^{-1}\text{K}^{-1}$ ), the consumption of the heat  
310 pump diminishes of the 1.99% as the pipe distance is increased from 35mm to 117 mm; on the other  
311 hand, if a highly conductive grout ( $\lambda_g = 5 \text{ Wm}^{-1}\text{K}^{-1}$ ) is used, this difference is reduced to the 0.64%,  
312 meaning that special grouts noticeably reduce the effect of an insufficient pipe spacing.

313

314 The fluid circulated into the closed pipe loop is usually a mixture of water and antifreeze. The flow  
315 rate and the physical properties of this fluid (viscosity, thermal capacity, thermal conductivity)  
316 influence the borehole thermal resistance [42]. The main drawbacks of increasing the concentration  
317 of the antifreeze additive are a noticeable increase of viscosity, a slight decrease of the thermal  
318 conductivity and an additional cost (say  $2\div 4 \text{ €/l}$ , depending on the kind of ethanol or glycol); in  
319 addition, the antifreeze is a potential source of contamination in case of a pipe leak, and the anti-  
320 corrosion additives can inhibit the bacterial degradation [43]. All these adverse side effects should  
321 be minimized when choosing the anti-freeze additive. Simulations have been carried out  
322 considering the most common anti-freeze mixtures: propylene glycol (PG) at 25% and 33% volume  
323 concentration, ethanol (ETH) at 24% vol., calcium chloride ( $\text{CaCl}_2$ ) at 20% weight concentration.  
324 Their physical properties are reported in Tab. 1, where also the boundaries of the laminar and of the  
325 turbulent regime are shown, since the thermal resistance is much smaller in turbulent one [42]. The

326 default flow rate is  $0.5 \text{ ls}^{-1}$ , which is a typical value for GSHPs. The results (Fig.4D and Fig.6C)  
 327 show that calcium chloride solutions permit to achieve an appraisable gain in the energy  
 328 performance (compared to PG25%, minimum temperature:  $+2.94^\circ\text{C}$ ; heat pump consumption: -  
 329 4.01%), due to their smaller viscosity and their higher thermal conductivity; in addition, it is much  
 330 cheaper than the other antifreeze additives. On the other hand, the use of saline solutions as a heat  
 331 carrier fluid requires the adoption of specific anti-corrosion components.  
 332 The other antifreeze mixtures show negligible variations of the fluid temperatures and of energetic  
 333 performances. As the thermal resistance diminishes when higher flow rates are circulated, seven  
 334 simulations (fluid: PG25%, flow rates:  $0.1 \div 0.7 \text{ ls}^{-1}$ ) have been run to quantify its contribution for a  
 335 better efficiency of the GSHP. We observe that the energy consumption of the heat pump is reduced  
 336 of the 4.4% between  $0.1$  and  $0.7 \text{ ls}^{-1}$ ; nevertheless, circulating larger flow rates implies also a higher  
 337 energy expense for the circulation pump. We have therefore quantified the distributed friction losses  
 338 along the 75m long using the explicit approximation of the Prandtl formula (Eq.6) for smooth pipes:

$$339 \quad \lambda_0 = \frac{0.25}{\left[ \log_{10} \left( \frac{5.7}{\text{Re}^{0.9}} \right) \right]^2}$$

340 6

341 where  $\lambda_0 = 2g \frac{d_{ip}}{u^2} \cdot J$  is the non dimensional friction loss,  $d_{ip}$  is the pipe internal diameter,  $g$  is the  
 342 gravity acceleration,  $J$  is the hydraulic gradient in the pipes.

343 The energy consumption of the circulation pump increases rapidly with the fluid flow rate ( $Q_f$ ):

$$344 \quad CPC = \frac{J \cdot 2L \cdot \rho_f \cdot g \cdot Q_f}{\eta} \cdot t_{func} = \frac{16 \cdot \lambda_0 \cdot L \cdot \rho_f \cdot g}{\eta \cdot \pi^2 \cdot D^4} Q_f^3 \cdot t_{func}$$

345 7

346 where  $\rho_f$  is the density of the heat carrier fluid,  $L$  is the BHE length [L] and  $t_{func}$  is the operation  
 347 time per year. An energy yield  $\eta = 0.8$  has been assumed for the calculation of  $CPC$ .



348 Fig.8 shows the strong impact of the flow rate on the total energy consumption (circulation and heat  
349 pump). In particular, a strong variation occurs when switching from laminar to transition regime  
350 (between 0.2 and 0.3 l/s), with a reduction of 2.07% for the total energy consumption, while the  
351 minimum values lie in a range of flow rates (for this case, 0.3÷0.5 ls<sup>-1</sup>). Noticeable differences are  
352 observed in the minimum temperature, meaning that higher flow rates can be adopted when larger  
353 amounts of heat are extracted from the soil, in order to avoid the freezing of the ground, or to  
354 reduce its extent.

355

356 While the design parameters can be determined with an acceptable precision, the real issue of  
357 GSHP modelling is the knowledge of the physical parameters of the soil. The heat transport around  
358 the BHE is mainly conductive, especially if no significant groundwater flow occurs, therefore the  
359 most important soil physical parameter is the thermal conductivity of the porous medium  $\lambda_{ij}^{cond}$  (see  
360 Eq.2).

361 The thermal conductivity of the solid matrix ( $\lambda_s$ ) is the parameter which can vary in the widest  
362 range, depending on the lithology, the grain size, the water saturation etc.. A wide range of values  
363 has been explored in the simulations (1÷3 Wm<sup>-1</sup>K<sup>-1</sup>), and the graphs of the cumulate distribution of  
364 the fluid temperatures (Fig.5E) and of the heat pump energy consumption (Fig.6D) show that  
365 thermal conductivity has a very strong influence on the performances of the system, compared to  
366 the BHE length. Especially in smaller installations, this parameter is not measured in situ, but low-  
367 precision data from literature are adopted (e.g. the German norm VDI 4640 [44]). For example, the  
368 thermal conductivity of a moraine ranges between 1 and 2.5 Wm<sup>-1</sup>K<sup>-1</sup>, for which we observe a  
369 difference of 5.66°C in the minimum temperature, and 12.5% in the power consumed by the heat  
370 pump. An imprecise knowledge of this parameter results therefore in a strong uncertainty in the  
371 simulation of the plant, which has to be overcome e.g. with a Thermal Response Test [45].

372

373 The presence of a subsurface flow has been proved to be beneficial for the performances of closed-  
374 loop geothermal heat pumps. Indeed, groundwater flow activates advection and thermal dispersion,  
375 enhancing the heat transport around the BHE and spreading the thermal disturbance further away.  
376 Chiasson et al. [25] demonstrated that the advection has a considerable impact only in coarse-  
377 grained soil (sands and gravels) and in fractured aquifers (e.g. karst limestone), while Wang et al.  
378 [26] stressed the importance of the saturated thickness, which can vary through the year, influencing  
379 also the results of Thermal Response Tests [12]. A set of simulations with different flow velocities  
380 and saturated thicknesses has been run therefore to quantify the positive effect of groundwater flow  
381 in a typical sand aquifer ( $K = 10^{-4} m/s$ ).

382 As shown in Fig.5B-C and Fig.6E, the influence of the Darcy velocity on the performances of the  
383 system is much stronger than the variation induced by different saturated thicknesses. This means  
384 that the contribution of the advection can be taken into account, but precise values are needed to  
385 avoid undersized design; on the other hand, variations in the saturated thickness - e.g. due to  
386 seasonal level variations in surface water bodies - do not exert a strong influence on the operation  
387 of GSHPs, if the gradient does not experience significant variations.

388  
389 When modelling heat transport in an aquifer, one should consider also the dispersion, which is a  
390 strong mechanism of heat transport. The thermal dispersivity has been considered as a scale-  
391 dependent parameter, as reported in literature [46]. Sethi and Di Molfetta [21] adopted  $\alpha_L = 10 m$   
392 and  $\alpha_T = 1 m$  for the heat transport simulation around a municipal solid waste landfill. Erol [47]  
393 assumed  $\alpha_L = 2 m$  and  $\alpha_T = 0.2 m$  for the simulation of a 100 m long BHE. Molina-Giraldo et al.  
394 [48] analyzed the extension of the thermal plume downstream of a BHE, for different values of  
395 groundwater flow Darcy velocity ( $q = 10^{-8} \div 10^{-5} m/s$ ) and for different values of thermal  
396 dispersivity ( $\alpha_L = 0 \div 2 m$ ), discovering that thermal dispersion reduces the extent of a reference  
397 isotherm (e.g.  $+1^\circ C$ ) of the deviation from the undisturbed soil temperature.

398 Wagner et al. [49] also analyzed the effect of  $\alpha_L$  for Thermal Response Tests in presence of  
399 groundwater flow, concluding that thermal dispersion can lead to a strong overestimation of the  
400 thermal conductivity of the soil. This is confirmed by the cumulate distribution of the average fluid  
401 temperatures for a Darcy velocity of 4.32 m/day (Fig.5D), which prove that the thermal dispersion  
402 is a great factor of uncertainty when modelling BHE fields in presence of subsurface flow. A rule of  
403 thumb that is usually employed in the solute transport [50] is:

$$\alpha_L = 0.1L_p$$

404  
405 8  
406 where  $L_p$  is the spatial scale of the dispersion phenomenon. The concept of “scale” is not  
407 univocally defined for GSHPs: using the BHE diameter (i.e.  $\alpha_L = 0.1m$  or less) or its length (i.e.  
408  $\alpha_L = 10m$ ) would imply a difference of some  $8\div 10^\circ\text{C}$  for the minimum fluid temperature and more  
409 than 15% for the electricity consumption of the heat pump (see Fig.6F). It is therefore advised not  
410 to rely on thermal dispersion when designing BHE fields, until field tests will be carried to estimate  
411 the thermal dispersivity in real-scale setups: especially if a thick and conductive aquifer is present,  
412 the overestimation of the thermal dispersivity would lead to an under-dimensioning of the GSHP  
413 with a detrimental effect on its long-term sustainability.

414

#### 415 **4. Conclusions**

416 In this work, the most important parameters which influence the performances of Ground Source  
417 Heat Pumps have been thoroughly analyzed, running long-term simulations and estimating the  
418 energy consumption of the heat pump for each setting. Most of these factors have been already  
419 analyzed in other works, but none of them considered all the parameters together, using the same  
420 modelling framework and considering the effect on the lifetime of a GSHP. The analysis of the  
421 BHE design parameters (length, pipe spacing, fluid, grout) permits to understand which are the  
422 margins of improvement, while the physical parameters of the soil (thermal conductivity and

423 dispersivity, groundwater flow) have been analyzed in order to understand their effect on the  
424 uncertainty in the project phase.

425 The results of the simulations prove that the length of the BHE is the most important parameter in  
426 the design of a GSHP. Indeed, increasing the borehole depth results in a reduction of the thermal  
427 disturbance in the subsoil and therefore to achieve a higher efficiency of the heat pump, but also a  
428 larger investment is needed for the installation.

429 An optimum length should be found, which minimizes the total cost over the plant lifetime,  
430 considering also the trend of increase of the unit cost of electricity. While the drilled depth has an  
431 appraisable impact on the initial investment, there are also other important factors to be considered  
432 for the optimization of BHEs, like the pipe arrangement, the grout and the heat carrier fluid. A large  
433 pipe spacing and a highly conductive grout, reducing the heat losses in the heat exchange with the  
434 soil, achieves an appraisable reduction of the energy costs for the heat pump with a negligible  
435 expense, compared to the borehole drilling. For the circulation pump, a trade-off can be found for  
436 the choice of the correct flow rate for the heat carrier fluid, allowing the minimization of both the  
437 energy losses due to the thermal resistance and the friction losses due to the circulation of the fluid.  
438 The antifreeze and its concentration heavily influence the energy performance of GSHPs, in  
439 particular the borehole resistance and the power consumed by the auxiliary plants. The saline  
440 solutions, with a smaller viscosity compared to ethanol and glycols, permit to reduce all these  
441 energy losses, although special components are needed to avoid corrosion problems. Optimizing the  
442 design and the installation of BHEs is useless without a thorough characterization of the subsoil,  
443 which has a large influence on the performances of these systems. When no groundwater flow  
444 occurs, the thermal conductivity is the most important parameter for the dimensioning of BHEs.  
445 The technical literature provides wide ranges of the thermal conductivity for each lithology, which  
446 can vary due to porosity, saturation and other factors; in-situ Thermal Response Tests are therefore  
447 strongly advised for large plants to avoid under or over dimensioning. The advection enhances the  
448 performances of GSHP, and the groundwater flow should be taken into account using conservative

449 values of hydraulic conductivity and gradient, unless they are known by field tests. On the other  
450 hand, it is risky to consider also the beneficial effect of heat dispersion, because the thermal  
451 dispersivity is still scarcely known in real-scale BHEs. In situ tests to estimate these parameters  
452 would be highly desirable to simulate the behaviour of BHE fields with a better precision.

453 **References**

- 454 [1] R. Curtis, J. Lund, B. Sanner, L. Rybach, G. Hellstrom, Ground Source Heat Pumps -  
455 Geothermal Energy for Anyone, Anywhere: Current Worldwide Activity, in: World Geothermal  
456 Congress, Antalya (Turkey), 2005, pp. 9.
- 457 [2] EUROBSERV'ER, The state of renewable energies in Europe - 11th EurObserv'ER Report, in,  
458 EUROBSERV'ER, 2011, pp. 254.
- 459 [3] W. Goetzler, R. Zogg, H. Lisle, J. Burgos, Ground-source heat pumps: overview of the market  
460 status, barriers to adoption, and options for overcoming barriers, in, U.S. Department of Energy,  
461 2009.
- 462 [4] D. Saner, R. Juraske, M. Kübert, P. Blum, S. Hellweg, P. Bayer, Is it only CO<sub>2</sub> that matters? A  
463 life cycle perspective on shallow geothermal systems, *Renewable and Sustainable Energy Reviews*,  
464 14 (2010) 1798-1813.
- 465 [5] P.F. Healy, V.I. Ugursal, Performance and economic feasibility of ground source heat pumps in  
466 cold climate, *International Journal of Energy Research*, 21 (1997) 857-870.
- 467 [6] V. Badescu, Economic aspects of using ground thermal energy for passive house heating,  
468 *Renewable Energy*, 32 (2007) 895-903.
- 469 [7] S. Blumsack, A. Kleit, S.W. Smith, Evaluation of federal and state subsidies for ground-source  
470 heat pumps, *Energy Efficiency*, 5 (2012) 321-334.
- 471 [8] L.R. Ingersoll, Theory of the ground pipe source for the heat pump, *ASHVE Transactions*, 54  
472 (1948) 339-348.
- 473 [9] H.G. Carslaw, J.C. Jaeger, *Conduction of heat in solids*, Cambridge, UK, 1946.
- 474 [10] D. Marcotte, P. Pasquier, F. Sheriff, M. Bernier, The importance of axial effects for borehole  
475 design of geothermal heat-pump systems, *Renewable Energy*, 35 (2010) 763-770.
- 476 [11] H.J.L. Witte, Error analysis of thermal response tests, *Applied Energy*, 109 (2013) 302-311.
- 477 [12] Ş. Bozdağ, B. Turgut, H. Paksoy, D. Dikici, M. Mazman, H. Evliya, Ground water level  
478 influence on thermal response test in Adana, Turkey, *International Journal of Energy Research*, 32  
479 (2008) 629-633.
- 480 [13] V. Wagner, P. Blum, M. Kübert, P. Bayer, Analytical approach to groundwater-influenced  
481 thermal response tests of grouted borehole heat exchangers, *Geothermics*, 46 (2013) 22-31.
- 482 [14] P. Eskilson, *Thermal Analysis of Heat Extraction Boreholes*, in, Lund University (Sweden),  
483 1987.
- 484 [15] G. Hellstrom, B. Sanner, *Earth Energy Designer, User Manual Version 2.0*, 2000.
- 485 [16] J.D. Spitler, GLHEPRO - A design tool for commercial building ground loop heat exchangers,  
486 in: 4th International Heat Pumps in Cold Climates Conference, Aylmer, Quebec, 2000.
- 487 [17] N. Diao, Q. Li, Z. Fang, Heat transfer in ground heat exchangers with groundwater advection,  
488 *International Journal of Thermal Sciences*, 43 (2004) 1203-1211.
- 489 [18] T.V. Bandos, Á. Montero, E. Fernández, J.L.G. Santander, J.M. Isidro, J. Pérez, P.J.F.d.  
490 Córdoba, J.F. Urchueguía, Finite line-source model for borehole heat exchangers: effect of vertical  
491 temperature variations, *Geothermics*, 38 (2009) 263-270.
- 492 [19] N. Molina-Giraldo, P. Blum, K. Zhu, P. Bayer, Z. Fang, A moving finite line source model to  
493 simulate borehole heat exchangers with groundwater advection, *International Journal of Thermal  
494 Sciences*, 50 (2011) 2506-2513.
- 495 [20] J. Hecht-Mendez, N. Molina-Giraldo, P. Blum, P. Bayer, Evaluating MT3DMS for Heat  
496 Transport Simulation of Closed Geothermal Systems, *Ground Water*, 48 (2010) 741-756.
- 497 [21] R. Sethi, A. Di Molfetta, Heat transport modeling in an aquifer downgradient a municipal solid  
498 waste landfill in Italy, *American Journal of Environmental Sciences*, 3 (2007) 106-110.
- 499 [22] C.D. Langevin, D.T. Thorne, A.M. Dausman, M.C. Sukop, W. Guo, SEAWAT Version 4: A  
500 Computer Program for Simulation of Multi-Species Solute and Heat Transport, in: USGS (Ed.) U.S.  
501 Geological Survey Techniques and Methods, 2008, pp. 39.

502 [23] H.J.G. Diersch, D. Bauer, W. Heidemann, W. Rühaak, P. Schätzl, Finite element modeling of  
503 borehole heat exchanger systems: Part 1. Fundamentals, *Computers and Geosciences*, 37 (2011)  
504 1122-1135.

505 [24] H.J.G. Diersch, D. Bauer, W. Heidemann, W. Rühaak, P. Schätzl, Finite element modeling of  
506 borehole heat exchanger systems. Part 2. Numerical simulation, *Computers and Geosciences*, 37  
507 (2011) 1136-1147.

508 [25] A.C. Chiasson, S.J. Rees, J.D. Spitler, A Preliminary Assessment of the Effects of Ground-  
509 Water Flow on Closed-Loop Ground-Source Heat Pump Systems, *ASHRAE Transactions*, 106  
510 (2000) 380-393.

511 [26] H.J. Wang, C.Y. Qi, H.P. Du, J.H. Gu, Thermal performance of borehole heat exchanger under  
512 groundwater flow: A case study from Baoding, *Energy and Buildings*, 41 (2009) 1368-1373.

513 [27] C.K. Lee, Effects of multiple ground layers on thermal response test analysis and ground-  
514 source heat pump simulation, *Applied Energy*, 88 (2011) 4405-4410.

515 [28] J.T. Chung, J.M. Choi, Design and performance study of the ground-coupled heat pump  
516 system with an operating parameter, *Renewable Energy*, 42 (2012) 118-124.

517 [29] F. Delaleux, X. Py, R. Olives, A. Dominguez, Enhancement of geothermal borehole heat  
518 exchangers performances by improvement of bentonite grouts conductivity, *Applied Thermal  
519 Engineering*, 33-34 (2012) 92-99.

520 [30] L. Jun, Z. Xu, G. Jun, Y. Jie, Evaluation of heat exchange rate of GHE in geothermal heat  
521 pump systems, *Renewable Energy*, 34 (2009) 2898-2904.

522 [31] A. Michopoulos, N. Kyriakis, The influence of a vertical ground heat exchanger length on the  
523 electricity consumption of the heat pumps, *Renewable Energy*, 35 (2010) 1403-1407.

524 [32] H.J.G. Diersch, O. Kolditz, *FEFLOW Reference Manual*, DHI-Wasy, Berlin, 2002.

525 [33] H.J.G. Diersch, O. Kolditz, *FEFLOW 6 User Manual*, DHI-Wasy, Berlin, 2010.

526 [34] D. Bauer, W. Heidemann, H. Müller-Steinhagen, H.J.G. Diersch, Thermal resistance and  
527 capacity models for borehole heat exchangers, *International Journal of Energy Research*, 35 (2011)  
528 312-320.

529 [35] P. Eskilson, J. Claesson, Simulation model for thermally interacting heat extraction boreholes,  
530 *Numerical Heat Transfer*, 13 (1988) 149-165.

531 [36] R. Al-Khoury, P.G. Bonnier, Efficient finite element formulation for geothermal heating  
532 systems. Part II: Transient, *International Journal for Numerical Methods in Engineering*, 67 (2006)  
533 725-745.

534 [37] R. Al-Khoury, P.G. Bonnier, R.B.J. Brinkgreve, Efficient finite element formulation for  
535 geothermal heating systems. Part I: Steady state, *International Journal for Numerical Methods in  
536 Engineering*, 63 (2005) 988-1013.

537 [38] H.-J.G. Diersch, D. Bauer, W. Heidemann, W. Ruhaak, P. Schatzl, Finite element formulation  
538 for borehole heat exchangers in modeling geothermal heating systems by FEFLOW, in: *DHI-  
539 WASY (Ed.) FEFLOW White Papers*, Berlin, 2010.

540 [39] H.N. Pollack, S.J. Hurter, J.R. Johnson, Heat flow from the earth's interior: analysis of the  
541 global data set, *Reviews of Geophysics*, 31 (1993) 267-280.

542 [40] P. Blum, G. Campillo, T. Kölbl, Techno-economic and spatial analysis of vertical ground  
543 source heat pump systems in Germany, *Energy*, 36 (2011) 3002-3011.

544 [41] C. Lee, K. Lee, H. Choi, H.P. Choi, Characteristics of thermally-enhanced bentonite grouts for  
545 geothermal heat exchanger in South Korea, *Sci China Technol Sc*, 53 (2010) 123-128.

546 [42] D. Bauer, W. Heidemann, H. Müller-Steinhagen, H.J.G. Diersch, Thermal resistance and  
547 capacity models for borehole heat exchangers, *International Journal of Energy Research*, (2010)  
548 n/a-n/a.

549 [43] T. Klotzbücher, A. Kappler, K.L. Straub, S.B. Haderlein, Biodegradability and groundwater  
550 pollutant potential of organic anti-freeze liquids used in borehole heat exchangers, *Geothermics*, 36  
551 (2007) 348-361.

552 [44] VDI, VDI 4640 - Thermal use of underground, in: Blatt 1: Fundamentals, approvals,  
553 environmental aspects, 2000.

554 [45] S. Gehlin, Thermal Response Test - Method Development and Evaluation, in: Department of  
555 Environmental Engineering, Lulea University of Technology, Lulea (Sweden), 2002, pp. 191.

556 [46] G. de Marsily, Quantitative hydrogeology, Academic Press, San Diego (CA, USA), 1986.

557 [47] S. Erol, Estimation of heat extraction rates of GSHP systems under different hydrogeological  
558 conditions, in, University of Tübingen, 2011.

559 [48] N. Molina-Giraldo, P. Bayer, P. Blum, Evaluating the influence of thermal dispersion on  
560 temperature plumes from geothermal systems using analytical solutions, International Journal of  
561 Thermal Sciences, 50 (2011) 1223-1231.

562 [49] V. Wagner, P. Bayer, M. Kübert, P. Blum, Numerical sensitivity study of thermal response  
563 tests, Renewable Energy, 41 (2012) 245-253.

564 [50] A. Di Molfetta, R. Sethi, Ingegneria degli Acquiferi, Springer, 2012.

565

566



567 **Nomenclature**

568	$BHL$	Total annual BHE Heat Load (kWh y <sup>-1</sup> )
569	$BHL_i$	BHE Heat Load at the i-th time step (kW)
570	$c_f$	Groundwater specific heat (J kg <sup>-1</sup> K <sup>-1</sup> )
571	$c_s$	Aquifer solid matrix specific heat (J kg <sup>-1</sup> K <sup>-1</sup> )
572	$COP$	Coefficient of Performance of the heat pump (dimensionless)
573	$CPC$	Circulating Pump Consumption (kWh y <sup>-1</sup> )
574	$d_{ip}$	Internal pipe diameter (m)
575	$d_{op}$	External pipe diameter (m)
576	$g$	Gravity acceleration (m s <sup>-2</sup> )
577	$H$	Heat source/sink (W/m <sup>3</sup> )
578	$HPC$	Total annual Heat pump energy consumption (kW y <sup>-1</sup> )
579	$HPC_i$	Power consumed by the heat pump at the i-th time step (kW)
580	$-\frac{\partial h}{\partial x}$	Hydraulic gradient in the aquifer (dimensionless)
581	$J$	Hydraulic gradient in the BHE pipes (dimensionless)
582	$K$	Hydraulic conductivity of the aquifer (m s <sup>-1</sup> )
583	$L$	Length of the BHE (m)
584	$L_p$	Scale dimension (m)
585	$n_e$	Effective porosity or specific yield of the aquifer (dimensionless)
586	$Q_f$	Flow rate of the heat carrier fluid (l s <sup>-1</sup> )
587	$q$	Darcy velocity of groundwater flow (m s <sup>-1</sup> )
588	$q_i$	i-th component of the Darcy velocity (m s <sup>-1</sup> )

589	Re	Reynolds number (dimensionless)
590	RMSE	Root Mean Square Error
591	$T$	Temperature of the soil, both solid and fluid phase (°C)
592	$T_f$	Average fluid temperature (°C)
593	$t_{func}$	Functioning time of the circulation pump (d y <sup>-1</sup> )
594	$T_{in}$	Inlet fluid temperature (°C)
595	$T_{out}$	Outlet fluid temperature (°C)
596	$T_s$	Soil temperature at the borehole interface (°C)
597	$u$	Flow velocity in the BHE pipes (m s <sup>-1</sup> )
598	$w$	Distance between the centres of the pipes in a BHE (m)
599	<b>Greek letters</b>	
600	$\alpha_L$	Longitudinal thermal dispersivity (m)
601	$\alpha_T$	Transverse thermal dispersivity (m)
602	$\varepsilon$	Porosity of the soil (dimensionless)
603	$\eta$	Energy yield (dimensionless)
604	$\lambda_0$	Non-dimensional friction loss (dimensionless)
605	$\lambda_f$	Thermal conductivity of the heat carrier fluid (W m <sup>-1</sup> K <sup>-1</sup> )
606	$\lambda_g$	Thermal conductivity of the grout (W m <sup>-1</sup> K <sup>-1</sup> )
607	$\lambda_p$	Thermal conductivity of the BHE pipes (W m <sup>-1</sup> K <sup>-1</sup> )
608	$\lambda_s$	Thermal conductivity of the solid matrix of the soil (W m <sup>-1</sup> K <sup>-1</sup> )
609	$\lambda_w$	Groundwater thermal conductivity (W m <sup>-1</sup> K <sup>-1</sup> )
610	$\lambda_{ij}^{cond}$	Thermal conductivity for conduction (W m <sup>-1</sup> K <sup>-1</sup> )

611	$\lambda_{ij}^{disp}$	Thermal conductivity for dispersion ( $\text{W m}^{-1} \text{K}^{-1}$ )
612	$\rho_f$	Density of the heat carrier fluid ( $\text{Kg m}^{-3}$ )
613	$\rho_s$	Density of the solid matrix of the soil ( $\text{Kg m}^{-3}$ )
614	$\rho_w$	Density of groundwater ( $\text{Kg m}^{-3}$ )
615	$(\rho c)_f$	Thermal capacity of the heat carrier fluid ( $\text{J m}^{-3} \text{K}^{-1}$ )
616	$(\rho c)_g$	Thermal capacity of the grout ( $\text{J m}^{-3} \text{K}^{-1}$ )
617	$(\rho c)_s$	Thermal capacity of the solid matrix of the soil ( $\text{J m}^{-3} \text{K}^{-1}$ )
618	$(\rho c)_w$	Thermal capacity of the solid matrix of the soil ( $\text{J m}^{-3} \text{K}^{-1}$ )

619 **Tables**

<b>Fluid</b>	$T_{freezing}$ [°C]	$\lambda_f$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	$c_f$ [Jkg <sup>-1</sup> K <sup>-1</sup> ]	$\rho_f$ [kgm <sup>-3</sup> ]	$\mu_f$ [mPas]	$Q_{lam}$ [Is <sup>-1</sup> ]	$Q_{turb}$ [Is <sup>-1</sup> ]
Prop.Glycol 25%	-10	0.45	3974	1026	5.51	0.252	1.097
Ethanol 24.4%	-15	0.426	4288	972	5.85	0.283	1.229
Prop.Glycol 33%	-15	0.416	3899	1015	8.17	0.378	1.644
CaCl <sub>2</sub> 20%	-20	0.54	3030	1186	4	0.158	0.689

620

621 **Tab. 1 – Physical properties of the anti-freeze solutions used in the simulations: solidification temperature**  
 622 **( $T_{freezing}$ ), thermal conductivity ( $\lambda_f$ ), specific heat ( $c_f$ ), density ( $\rho_f$ ), dynamic viscosity ( $\mu_f$ ), upper boundary**  
 623 **flow rate for the laminar regime ( $Q_{lam}$ ) and lower boundary flow rate for the turbulent regime ( $Q_{turb}$ ).**

624

<b>Parameter</b>	<b>Values</b>
6 kW heat pump + installation	6000€
BHE drilling + installation	70 €/m
Unit cost of electricity	0.22 €/kWh
Increment of the unit cost of electricity	0%, 1%, 3%, 5%

625

626 **Tab. 2 – Installation and energy costs used for the optimization procedure of the BHE length.**

627

628 **Figure captions**

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

634

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

636

637 **Fig. 3 – A: Time series of the average fluid temperatures, detail of 5 years of simulation. B: Cumulate**  
638 **distribution of the average fluid temperatures in the heating seasons.**

639

640 **Fig. 4 – Cumulate distributions of the average fluid temperatures for different values of BHE length (A), pipe**  
641 **spacing (B), thermal conductivity of the grout (C) and heat carrier fluids (D).**

642

643 **Fig. 5 – Cumulate distributions of the average fluid temperatures for different values of the thermal conductivity**  
644 **of the solid matrix of the soil (A), groundwater flow Darcy velocity with no thermal dispersion (B), Darcy**  
645 **velocity and saturated thickness (C), thermal dispersivity (D).**

646

647 **Fig. 6 – Estimated annual heat pump energy consumption for different values of BHE length (A), pipe spacing**  
648 **and grout conductivity (B), heat carrier fluids (C), solid-phase soil thermal conductivity (D), groundwater flow**  
649 **Darcy velocity and saturated thickness (E) and thermal dispersivity (F).**

650

651 **Fig. 7 – Relative variation of the total cost of a GSHP over a lifetime of 30 years, for different BHE lengths**  
652 **(50÷100m) and different increment rates of the unit cost of electricity (0÷5%).**

653

654 **Fig. 8 – Cumulate distributions of the average fluid temperatures (A) and electric power consumption of the heat**  
655 **pump and circulation pump (B) for different fluid flow rates.**

## Supporting information

**Tab. 1 – Summary of the results of the simulations: mean and RMSE of the average fluid temperature ( $T_f$ ), minimum values of the inlet temperature ( $T_{in}$ ), Seasonal Performance Factor (SPF) and annual Heat Pump Consumption (HPC).**

Parameter	value	Parameter	value	mean ( $T_f$ ) [°C]	RMSE ( $T_f$ ) [°C]	min ( $T_{in}$ ) [°C]	SPF [-]	HPC [kWh/y]
		BHE length [m]	50	1.83	5.69	-6.39	4.22	2845.8
			55	2.52	5.36	-5.34	4.29	2799.5
			60	3.07	5.01	-4.40	4.34	2765.6
			65	3.46	4.79	-3.94	4.37	2743.0
			70	4.14	4.54	-2.99	4.44	2704.0
			75	4.63	4.25	-2.24	4.48	2678.4
			80	4.99	4.06	-1.71	4.51	2661.4
			85	5.26	3.92	-1.49	4.53	2648.5
			90	5.62	3.76	-1.02	4.56	2631.3
			95	6.03	3.57	-0.47	4.60	2611.1
			100	6.21	3.46	-0.33	4.61	2604.2
pipe spacing [mm]	35	grout thermal conductivity [ $\text{Wm}^{-1}\text{K}^{-1}$ ]	1	0.34	7.16	-10.02	4.06	2956.2
	35		2	3.88	4.85	-3.74	4.42	2715.9
	35		3	4.18	4.59	-3.22	4.44	2701.2
	35		5	4.65	4.27	-2.27	4.48	2678.4
	55		1	0.62	6.92	-9.43	4.09	2931.5

Parameter	value	Parameter	value	mean ( $T_f$ ) [°C]	RMSE ( $T_f$ ) [°C]	min ( $T_{in}$ ) [°C]	SPF [-]	HPC [kWh/y]
	55		2	4.05	4.74	-3.46	4.43	2706.4
	55		3	4.29	4.49	-3.04	4.45	2695.5
	55		5	4.64	4.25	-2.20	4.48	2678.0
	80		1	1.32	6.39	-7.95	4.17	2877.8
	80		2	4.20	4.55	-3.10	4.45	2699.6
	80		3	4.60	4.27	-2.31	4.48	2680.9
	80		5	4.68	4.17	-2.06	4.48	2677.7
	100		1	4.23	4.77	-3.41	4.45	2695.1
	100		2	4.74	4.33	-2.33	4.49	2670.7
	100		3	4.67	4.18	-2.09	4.48	2677.6
	100		5	4.74	4.05	-1.97	4.48	2676.9
	117		1	3.09	4.95	-4.29	4.34	2766.9
	117		2	5.03	3.90	-1.36	4.51	2661.9
	117		3	5.07	3.86	-1.31	4.51	2660.7
	117		5	5.07	3.84	-1.32	4.51	2661.3
		heat carrier fluid	PG 33%	1.95	5.96	-6.74	4.23	2834.8
			ET 24%	1.98	5.79	-6.49	4.23	2835.0
			PG 25%	2.49	5.50	-5.62	4.29	2799.7
			CaCl <sub>2</sub> 20%	4.43	4.43	-2.68	4.47	2687.4
		solid matrix thermal conductivity [Wm <sup>-1</sup> K <sup>-1</sup> ]	1	-0.63	6.08	-9.36	3.91	3072.7
			1.5	1.32	5.47	-6.86	4.14	2895.8
			2	2.73	4.99	-4.72	4.30	2790.5

Parameter	value	Parameter	value	mean ( $T_f$ ) [°C]	RMSE ( $T_f$ ) [°C]	min ( $T_{in}$ ) [°C]	SPF [-]	HPC [kWh/y]
			2.5	3.60	4.64	-3.70	4.38	2737.5
			3	4.63	4.25	-2.24	4.48	2678.4
saturated thickness [m]	55	groundwater flow Darcy velocity [m/d]	0.864	5.28	4.37	-1.83	4.54	2640.8
			1.728	5.99	4.37	-1.39	4.61	2601.0
			1.32	6.85	4.17	-0.33	4.70	2552.5
			8.64	7.53	3.77	0.80	4.76	2520.7
			17.28	8.21	3.29	2.14	4.82	2491.9
groundwater flow Darcy velocity [m/d]	0.864	saturated thickness [m]	10	4.67	4.32	-2.27	4.48	2676.2
			20	4.91	4.31	-2.06	4.51	2662.4
			50	5.25	4.36	-1.83	4.54	2642.6
groundwater flow Darcy velocity [m/d]	8.64	saturated thickness [m]	10	5.73	4.23	-1.20	4.59	2615.7
			20	6.43	4.07	-0.54	4.66	2576.8
			50	7.41	3.82	0.62	4.75	2526.6
groundwater flow Darcy velocity [m/d]	0.864	longitudinal thermal dispersivity [m]	0.1	5.32	4.35	-1.82	4.55	2639.0
			0.2	5.35	4.33	-1.81	4.55	2637.7
			0.5	5.46	4.27	-1.74	4.56	2632.0
			1	5.61	4.20	-1.35	4.57	2624.1
			2	5.72	4.11	-1.26	4.58	2619.1
			5	6.32	3.78	-0.44	4.63	2589.9
groundwater flow Darcy velocity [m/d]	1.728	longitudinal thermal dispersivity [m]	0.1	6.04	4.34	-1.32	4.62	2598.7
			0.2	6.10	4.30	-1.27	4.62	2596.1
			0.5	6.23	4.20	-0.89	4.63	2589.8



Parameter	value	Parameter	value	mean ( $T_f$ ) [°C]	RMSE ( $T_f$ ) [°C]	min ( $T_{in}$ ) [°C]	SPF [-]	HPC [kWh/y]
			1	6.43	4.08	-0.80	4.65	2580.5
			2	6.62	3.91	-0.37	4.67	2572.3
			5	7.48	3.39	1.16	4.74	2534.0
groundwater flow Darcy velocity [m/d]	4.32	longitudinal thermal dispersivity [m]	0.1	6.91	4.14	-0.29	4.71	2550.0
			0.2	6.98	4.09	-0.26	4.71	2547.1
			0.5	7.26	3.91	0.29	4.73	2535.4
			1	7.60	3.68	0.93	4.76	2521.6
			2	8.09	3.33	1.86	4.80	2501.3
			5	8.94	2.78	3.44	4.86	2467.8

**Tab. 2 – Summary of the results of the simulations with different values of heat carrier fluid flow rate ( $Q_f$ ): mean and RMSE of the average fluid temperature ( $T_f$ ), minimum values of the inlet temperature ( $T_{in}$ ), Seasonal Performance Factor (SPF), annual heat pump consumption (HPC), circulating pump energy consumption (CPC) and total energy consumption (HPC+CPC).**

$Q_f$ [l/s]	mean ( $T_f$ ) [°C]	RMSE ( $T_f$ ) [°C]	min ( $T_{in}$ ) [°C]	SPF	HPC [kWh/y]	CPC [kWh/y]	HPC+CPC [kWh/y]
0.1	-0.52	7.34	-16.57	4.09	2932.4	1.3	2933.8
0.2	0.19	7.02	-11.68	4.13	2906.6	8.2	2914.8
0.3	1.71	5.96	-7.51	4.24	2830.6	24.0	2854.6
0.4	2.49	5.50	-5.62	4.29	2799.7	51.9	2851.6
0.5	2.76	5.24	-4.97	4.28	2800.9	94.5	2895.4
0.6	3.14	4.99	-4.17	4.30	2790.8	154.5	2945.3
0.7	3.14	4.94	-3.75	4.28	2803.1	234.4	3037.5

Fig.1

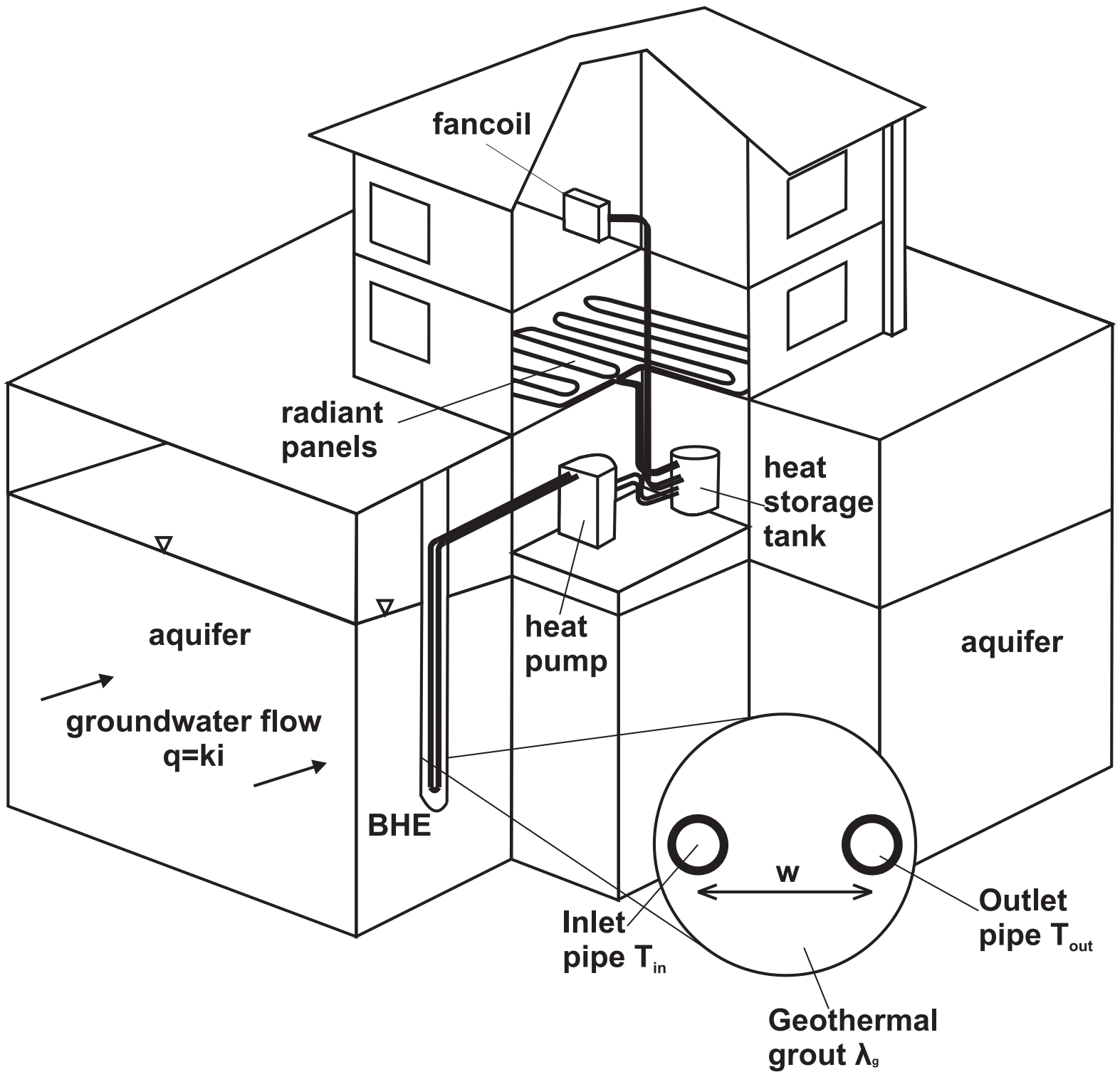


Fig.2

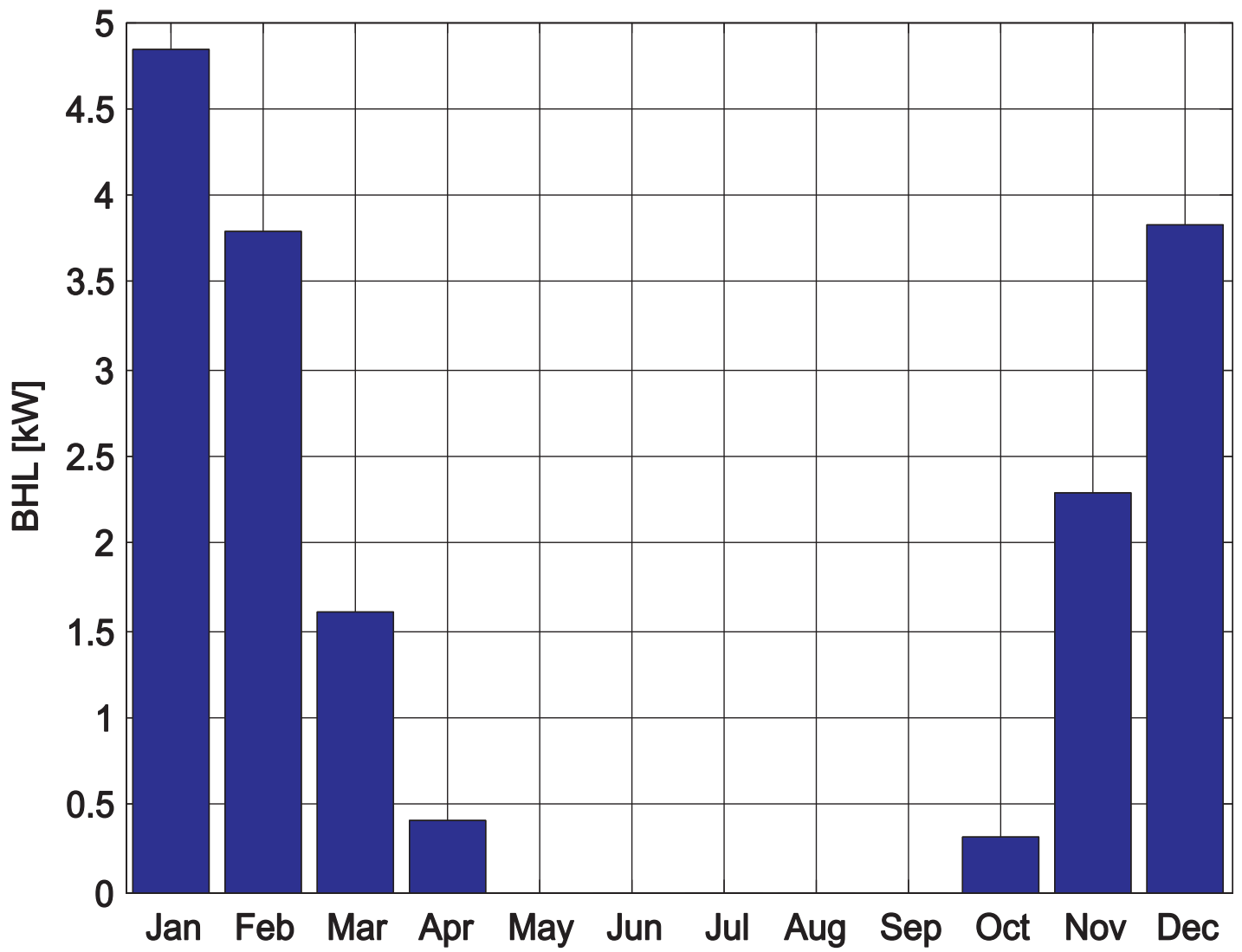


Fig.3

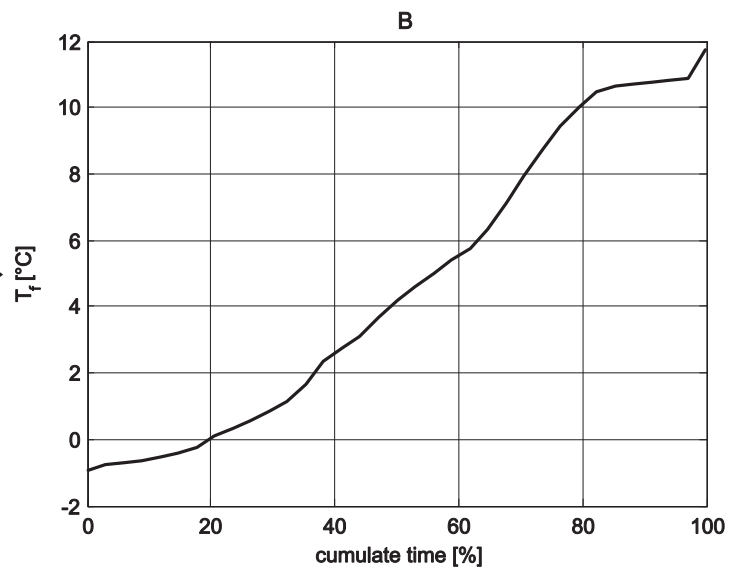
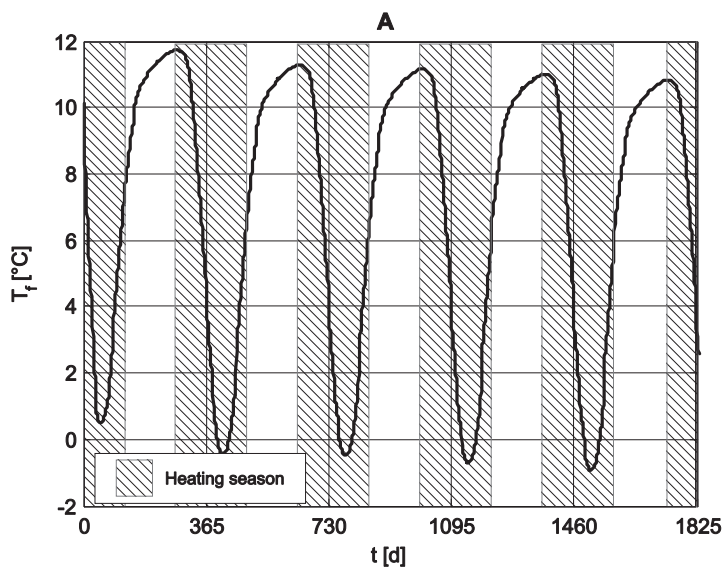


Fig.4

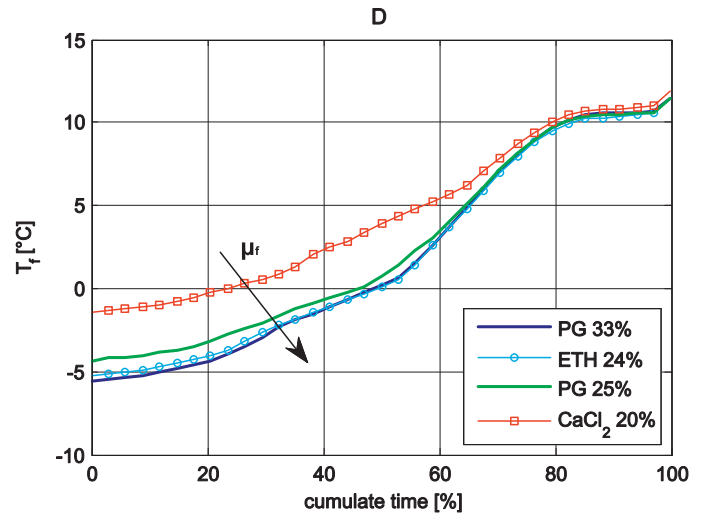
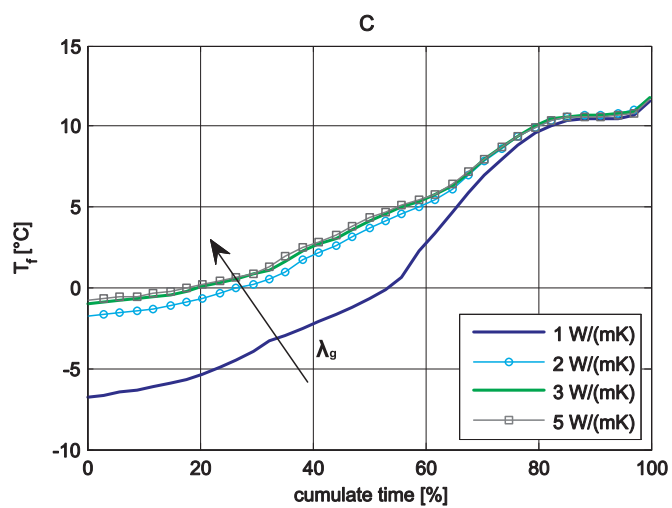
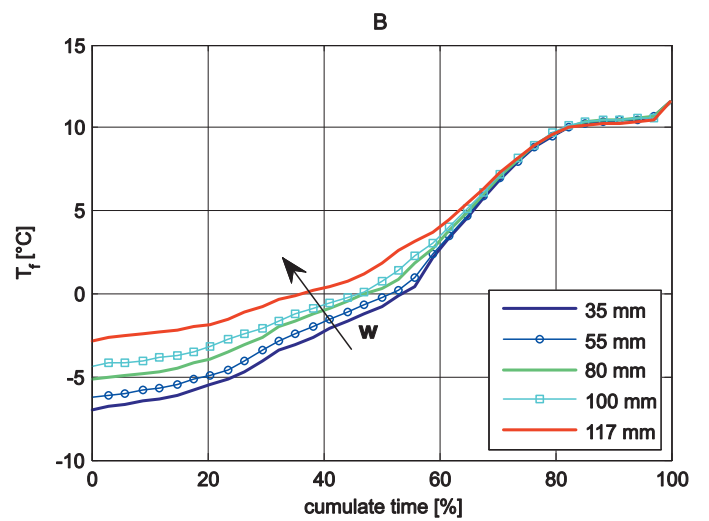
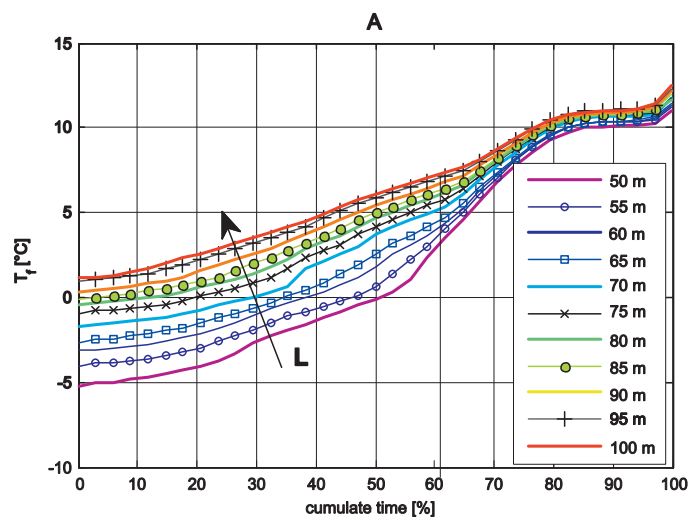


Fig.5

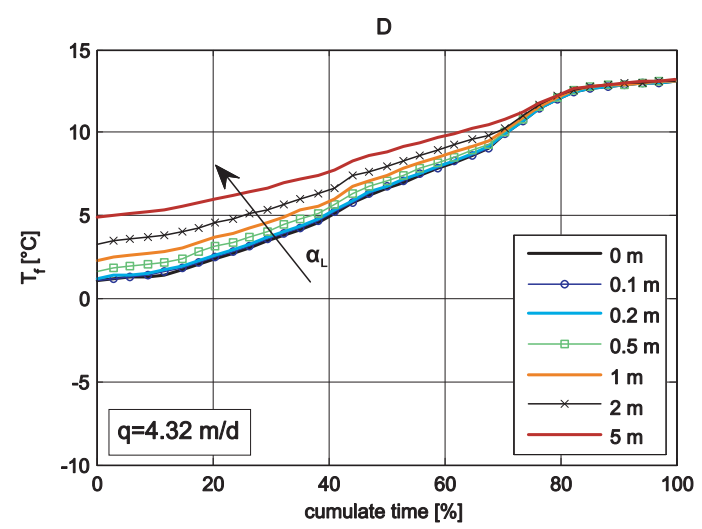
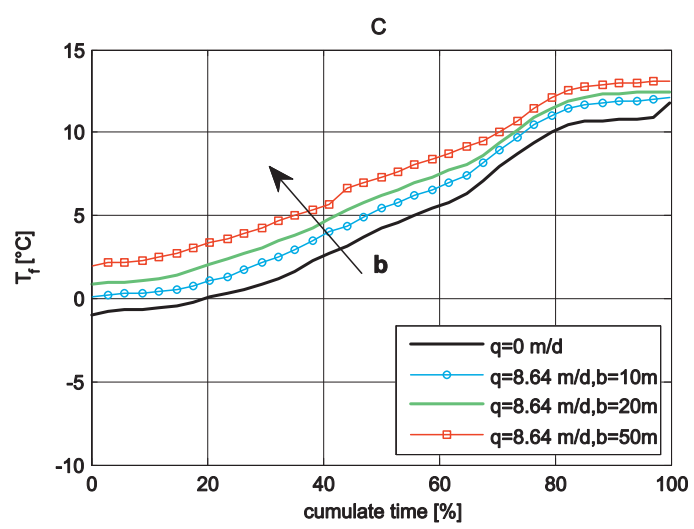
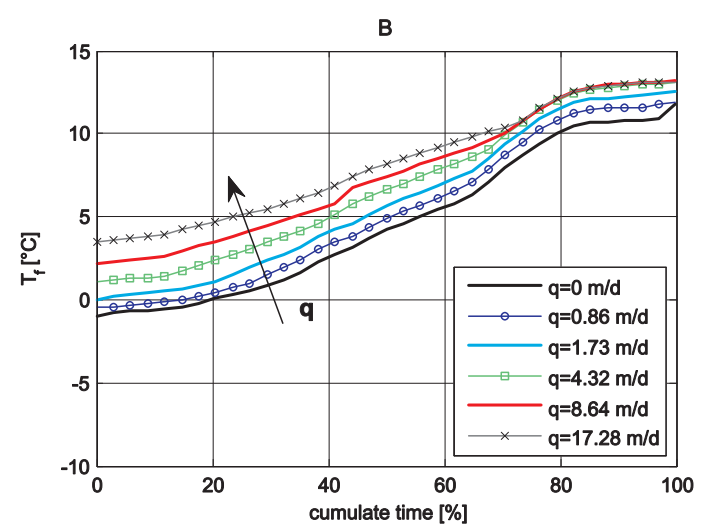
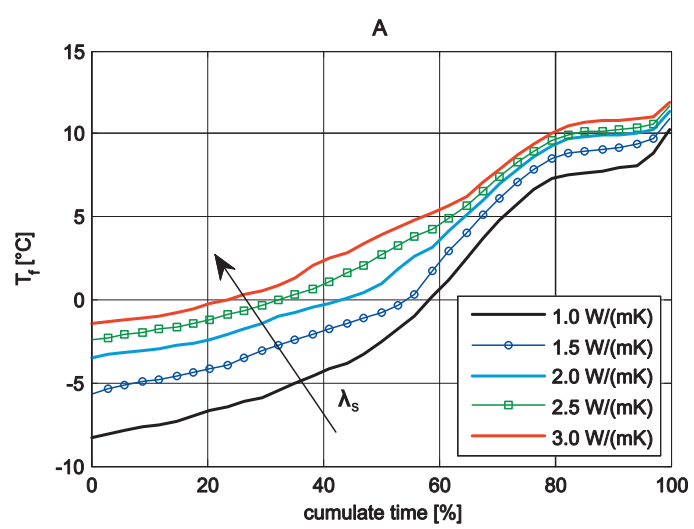


Fig.6

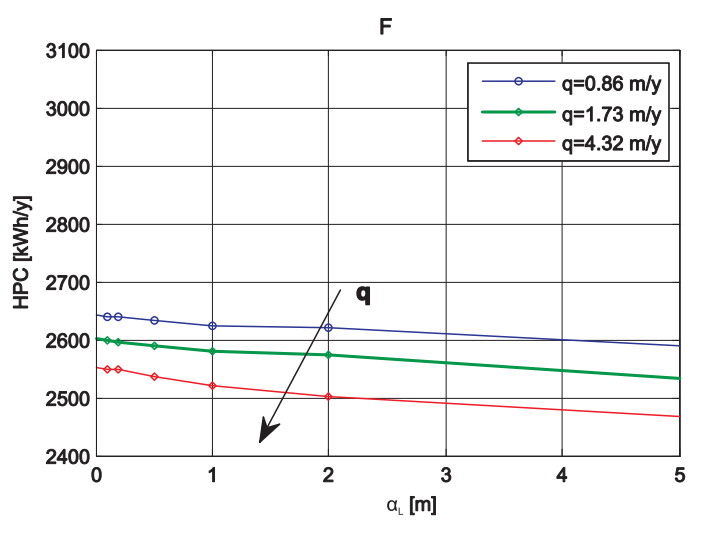
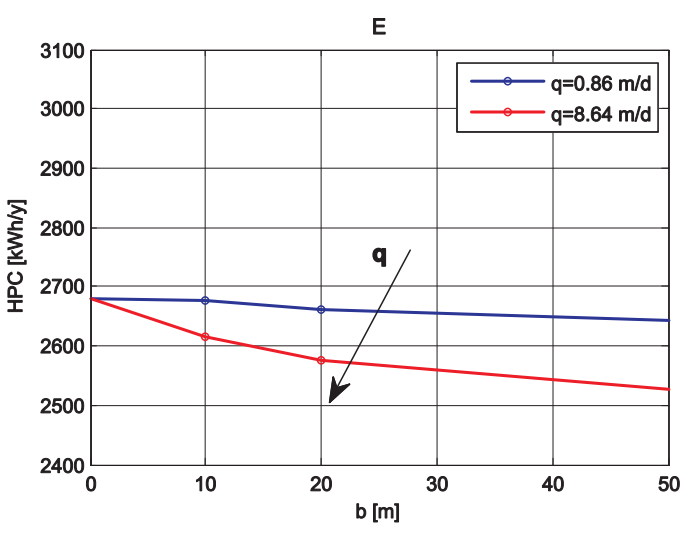
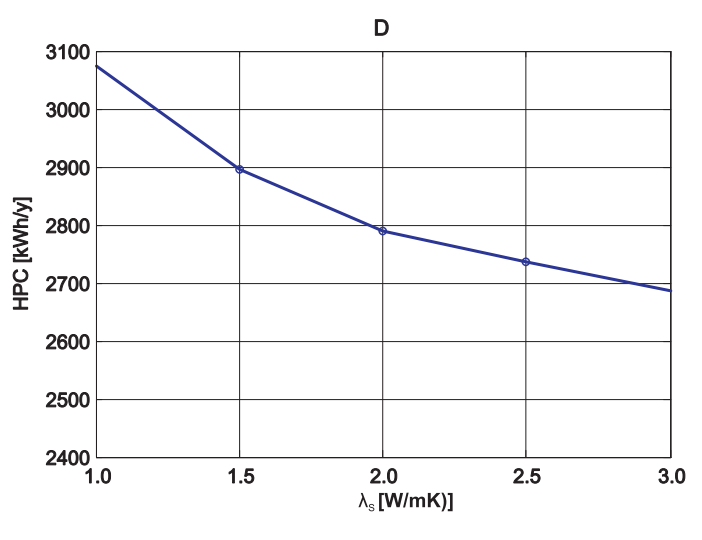
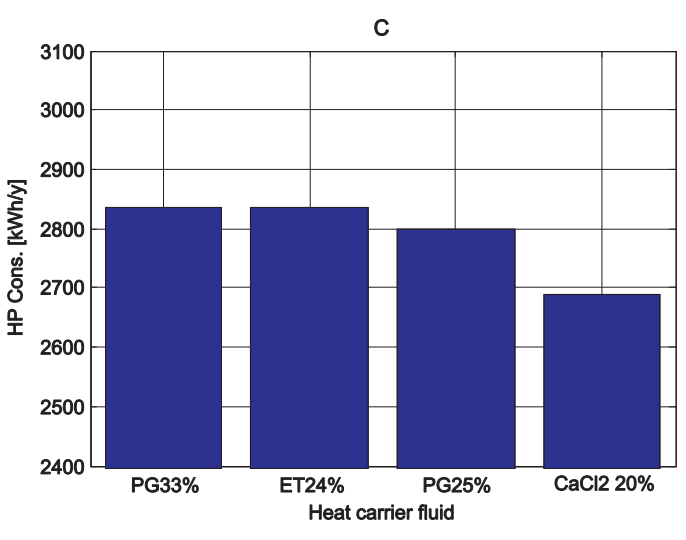
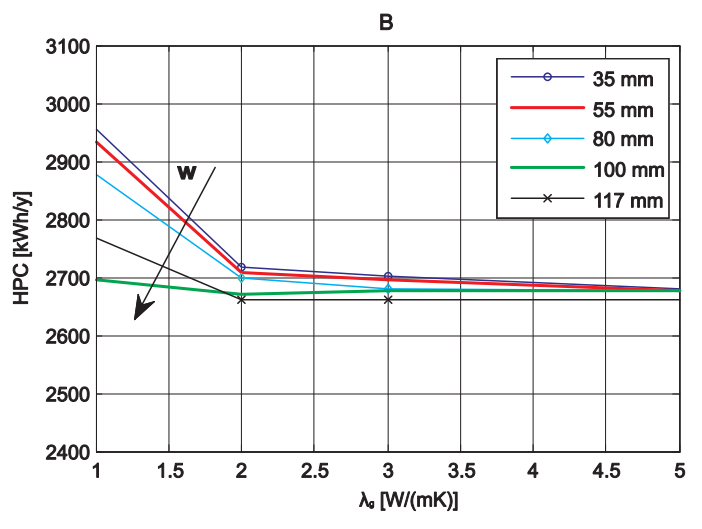
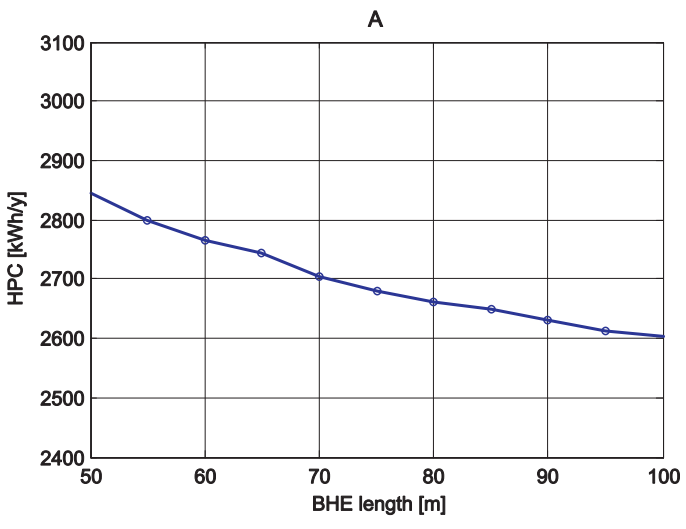




Fig.7

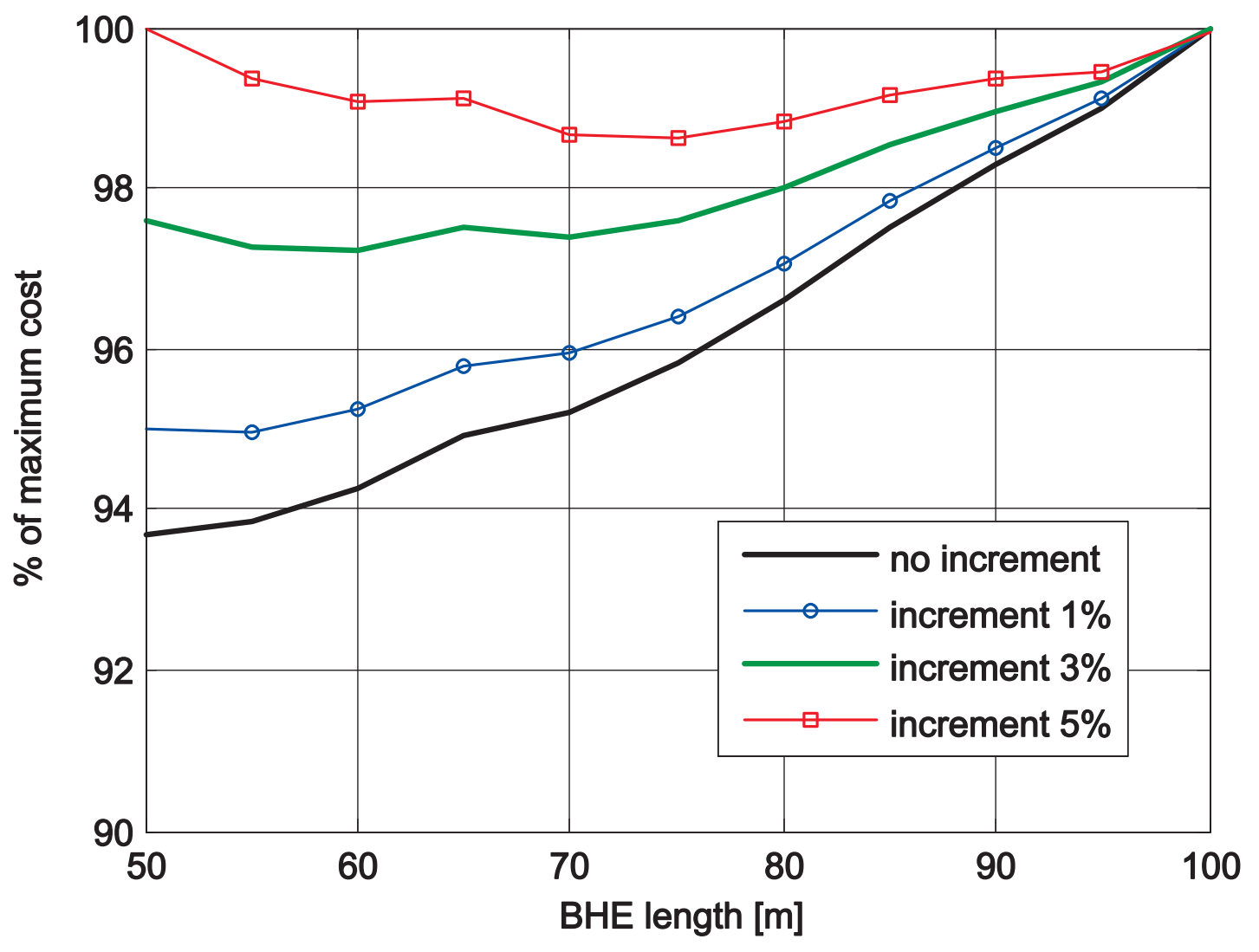


Fig.8

