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Research article

How a sensitive analysis on the coupling geology and borehole heat exchanger characteristics can improve the efficiency and production of shallow geothermal plants

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A B S T R A C T

Knowledge of the thermal behaviour around and throughout borehole heat exchangers (BHEs) is essential for designing a low enthalpy geothermal plant. In particular, the type of grout used in sealing the space between BHE walls and the pipes is fundamental for optimizing the heat transfer and minimizing the thermal resistance, thereby promoting the reduction of total drilling lengths and installation costs. A comparison between grouts with different thermal conductivities coupled with common hydrogeological contexts, was modelled for a typical one-year heating for continental climates. These data have been used for a sensitivity analysis taking into account different flow rates through pipes. The results highlight that in groundwater transient conditions, porous lithologies allow for greater heat power extractions to be obtained with an increasing grout thermal conductivity than limestone or clayey silt deposits do. Moreover, increasing the inlet flow rates through the pipe greatly improves the final heat power extraction. As a result, when the underground allows for high extraction rates, the use of high performing grouts is warmly suggested ensuring greater productions.

1. Introduction

Thermal energy demand for heating and cooling is continuously increasing worldwide, with geothermal heat pumps coupled with borehole heat exchangers (BHE) representing an economical and environmentally friendly alternative (Andreu et al., 2020). In geothermal closed loop systems, a polyethylene pipe is buried several metres beneath the ground (usually more than 100 m), representing the heat exchanger for a geothermal heat pump. When a significant difference between the energy extracted and rejected is designed, unfavourable changes in soil temperature could occur (Kurevija et al., 2010; Zhao et al., 2018). The global efficiency of this system depends on several factors among which the thermal exchange between pipes, grout and the ground is probably the most important. In this framework, the grout is the only factor that can be easily improved, aiming to hydraulically insulate the borehole and thermally optimise the exchange between the pipe and ground. In contrast, the ground is not an isotropic and homogeneous medium but is instead characterised by specific and variable thermophysical characteristics due to geothermal heat flux, lithology, porosity and presence of water (Chicco et al., 2019; Giordano et al., 2019), so that the ground behaves as fixed variable that cannot be changed to improve heat power extraction. Additionally, pipes can be coaxial, single, or double U shaped and made of steel or polyethylene so that variables increase, and thermal performances are not easy to forecast (Badenes et al., 2020).

Another parameter that can be modified, even during the BHE operation, is the flow rate of the heat transfer fluid.

Most of the previous studies mainly focused on the grout influence, without evaluating their iteration with the other components such as the flow rates of the heat transfer fluid inside pipes, and the hydrogeological conditions. This paper analyses some common geological situations in northern Italy and how the grout and flow rate can be changed to improve the efficiency of the entire ground source heat pump (GSHP) system.

Commercial software (Feflow; WASY DHI Group) for numerical simulations was used to define BHE performances during a heating season of 212 days (typically one year of heating for continental climatic conditions). In particular, the following variables were taken into account:

- 4 geothermal grouts with different thermal conductivities (in the range of commercial geothermal grouts);
- 3 distinct ground lithologies (clayey-silt, limestone and sand);

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- 3 groundwater conditions (dry, steady-state groundwater flow and transient groundwater flow);
- 3 different flow rates of the inlet heat transfer fluid through the pipes (20, 40, and 60 m^3/d)

Numerical simulations combining the above parameters were aimed at defining the conductive and advective heat transfer throughout and around the BHE, predicting the thermal disturbance in the ground around the BHE, and the entire GSHP performance.

2. A review of geothermal grout studies

Technological developments in recent years have addressed new materials that are able to enhance the BHE performance and are also thought to be new grouting mixtures. Many authors have studied conventional and experimental grouts for geothermal purposes, focusing on different aspects strictly linked to the entire borehole-ground system. For instance, Kurevija et al. (2017), have analysed the long-term impact (30 years) on the efficiency of the GSHP system. The grout influence on the borehole thermal resistance was considered, as well as the advantages in terms of cost benefits when using thermally enhanced grouts over conventional ones. By using different grouts, they observed temperature degradation over 30 years and they supposed it was due to the permanent subcooling of the ground, and the thermal interference between BHEs.

The relevant impact of the grout thermal conductivity on borehole thermal resistance depending on aquifer characteristics was highlighted in Alberti et al. (2017). Many authors have focused on the comparison between different mineralogical compositions of both experimental and conventional grouts, analysing their thermal and mechanical properties (Borinaga-Treviño et al., 2012; Blázquez et al., 2017; Viccaro, 2018; Mahmoud et al., 2021) combined with their hydration, density, and compressive strength as recently developed by Mascarin et al. (2022). Moreover, in-situ (Chicco et al., 2016; Verdoya et al., 2018) and lab tests (Indacoechea-Vega et al., 2015), also looking for the most suitable pumpability aimed at avoiding hydraulic and thermal discontinuities (Delaleux et al., 2012), were conducted to test the grout efficiencies. Direct evaluations of GSHP performances linked to the specific extractable heat and drilling costs, with the contribution of different conventional and experimental grouts, were also presented in Luo et al. (2020). Recently, Liang et al. (2022) evaluated some optimizing BHE operation modes affecting its performance: they compared grouts doped with some additives at a high thermal conductivity, together with heat transfer fluids composed of nanofluids and encapsulated phase change slurry.

On the other hand, more detailed studies based on numerical simulations show how specific types of grouts behave and how they can improve the overall BHE performances (Li et al., 2018; Kim and Ho, 2018; Badenes et al., 2020b; Van de Ven et al., 2021): in particular Kim and Ho (2018) proved how the GHE performances can increase with an increased thermal conductivity and specific heat capacity values of different types of grouting mixtures, during both continuous and intermittent GSHP operations.

3. Numerical simulations

Closed loop systems using BHEs can be modelled at different levels of detail, ranging from considering the heat source from a specific BHE boundary condition to fully discretised solutions. Even if difficult, time-consuming, and expensive, a preliminary selection of the best option is fundamental for a cost-effective design. One of the most commonly used software is FeFlow (WASY DHI Group) which allows for obtaining efficient results on the thermal exchange between geothermal pipes, grouting materials and the surrounding underground soils. Due to the possibility of introducing specific boundary conditions, the thermotechnical model and its relationship with the hydrogeological conditions can be detailed. FeFlow allows for the combination of the thermotechnical characteristics of a BHE (e.g. the inner and outer pipe diameters, its thermophysical properties, and the characteristics of the heat transfer fluid and of the grouting mixture), together with the groundwater and lithological conditions.

Starting from a geometrical model in which it is possible to define the geological context, a series of polygonal, linear, and punctual elements were defined. For each element, specific boundary conditions and parameters were assigned. A triangular super mesh was ascribed to the model to reproduce complex shapes as well as to easily change the level of refinement. To avoid irregularly shaped elements and the number of obtuse-angled triangles, further mesh smoothing was conducted. Additionally, a check for obtuse angles and triangles violating the Delaunay criterion was accomplished.

Due to the complexity of the high number of triangular elements, the Algebraic MultiGrid Solver (SAMG) was used, because it is the fastest and most robust solver. It shows a fast convergence and has proven to be efficient for typical problems over a wide range of applications. Its main advantage is its parallelization on multicore systems, as well as its more efficient solution algorithm (Diersch, 2009).

The modelled area was a 30 × 50 × 100 m square, in which 4 punctual elements (10 m spaced) represent BHEs. Calculations were computed on each active node of the finite element mesh and interpolated within them. The denser the mesh the better the numerical accuracy. Local refinement around the BHE was performed during its generation to obtain a greater mesh quality. Once the model was discretised in 2D, it was extended into a 3D model with prismatic elements using the “3D layer configuration” tool. The final model consists of six slices forming five layers at different depths over a total length of 100 m (Figure 1). For each layer, specific hydrogeological and thermotechnical parameters were set, with thermotechnical parameters summarized in Table 1.

Three common simplified ground conditions in northern Italy were used: i) limestones refer to the Rotzo Unit, a karst limestone geological formation (Low Jurassic) belonging to the “Calcari grigi” complex (Di Cuia et al., 2011); ii) clayey silts, which are Pleistocene alluvial deposits typical of the western portion of the Verona area (NE Italy; Mozzi, 2005); and iii) sand deposits, which mainly refer to the Pleistocene fluvioglacial deposits of the Torino area (NW Italy; Giordano et al., 2016). Data from these three different hydrogeological contexts come from direct investigations of real geothermal plants. Understanding how these grounds can interact with thermotechnical characteristics could be of great interest in defining the entire thermal efficiency of a geothermal plant.

An undisturbed ground temperature of 14 °C was considered for all domains due to the absence of geothermal anomalies in the studied areas.

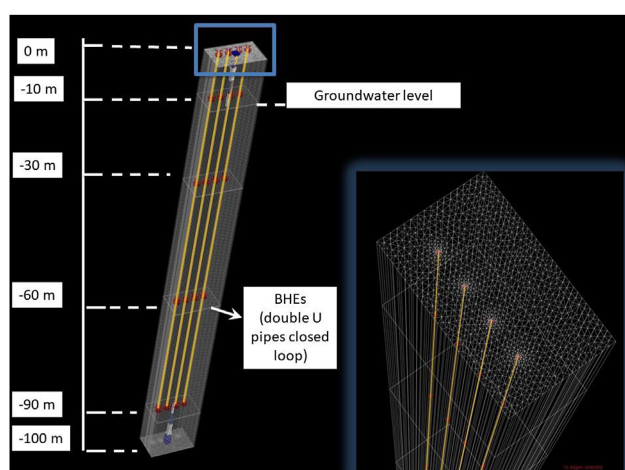

Figure 1. Tridimensional view of the whole domain divided by 6 slices at different depths; groundwater and borehole heat exchangers are the other represented elements. On the right side, a detail of the first slice, with the triangular mesh around BHEs (top view).

Table 1. Thermo-physical characteristics of lithologies used in the model. Keys: λ = Thermal Conductivity, T = Temperature, K=Hydraulic Conductivity, φ = Porosity, Cp = specific heat capacity; ρcp, thermal capacity.

Ground Lithology	Λ ($W \cdot m^{-1}K^{-1}$)	T (°C)	K (m/d)	Φ (%)	Cp ($J*Kg^{-1}*K^{-1}$)	ρcp ($KJ*m^{-3}*K^{-1}$)
Clayey Silt (CS)	0.8	14	$1\ 10^{-6}$	5	880	2200
Limestone (L)	2.6	14	$1\ 10^{-4}$	10	750	2000
Sand (S)	1.8	14	$1 \cdot 10^{-2}$	30	775	2050

The inlet temperature of the heat transfer fluid (water) in the pipes was fixed at 4 °C. Choosing of water instead of anti-freezing fluids is mainly linked to some environmental issues for which local authorities do not recommend their use. The heat power extraction obtained in this work is approximately 30% lower than that reported in the literature (for example, referred to VDI-Richtlinie 2010). This can be fully attributed to the differences in the fluid inlet temperature between water and anti-freezing fluids (4 °C instead of the more common 1 °C).

Different groundwater conditions were hypothesised, simulating both dry (D) and wet situations. In "wet" simulations, the groundwater level was set at -10 m from ground level and two scenarios were considered: the first one (steady-state groundwater flow - SW) implies a sutured medium without groundwater movement, and the second one (transient groundwater flow- TW) assumes a specific groundwater velocity defined by peculiar boundary conditions (BC) as well as a set of linear equations, based on the Darcy's law. A uniform hydraulic gradient of 3% and a N–S groundwater direction were assumed. The temperature of the BC was also defined following the same N–S groundwater flow direction. The groundwater temperature was set in equilibrium with that of the ground, equal to 14 °C.

Each simulation consisted of four BHEs with double-U geothermal pipes commonly used in Italy for low enthalpy geothermal plants, and thus with conventional characteristics as summarised in Table 2. For each borehole, a different grout was set reflecting commercial grout characteristics (G1 = 0.5, G2 = 1.0, G3 = 1.5 and G4 = 2.0 W $m^{-1}K^{-1}$).

Typical flow rates through pipes of 20, 40 and 60 m^3/d were also modelled. The heat transfer fluid (pure water without propylene-glycol) properties are as follows: thermal conductivity $\lambda = 0.58$ W $m^{-1}K^{-1}$, volumetric heat capacity c = 4190 J/m^3/K, and fluid dynamic viscosity $\tau = 3 \cdot 10^{-3}$ kg/m/s.

The Al-Khoury approach for transient groundwater conditions (Al-Khoury and Bonnier, 2006) was used to better define the entire heat transfer model throughout and around the BHE. This approach is based on a series of governing differential equations also adapted for transient groundwater conditions in porous mediums affected by air temperature, thermal conductivity of the pipe and of the grout material, as well as the thermal properties of the heat transfer fluid flowing throughout the pipe. Additionally, it provides higher accuracy for short-term predictions in time ranges smaller than hours, especially in conditions with quickly changing inflow temperature.

Table 2. BHE characteristics. Keys: P is the BHE depth; D is the BHE diameter; d_{in} and d_{out} are the inner and outer pipe diameters; b_{in} and b_{out} represent the inner and outer pipe thicknesses; λ_{in} and λ_{out} are the inner and outer pipe thermal conductivities, Σ is the spacing between the center of each pipe; B is the spacing between BHEs.

Pipes configuration	Double U
L (m)	90
d_{in} (m)	0.026
b_{in} (m)	0.0023
d_{out} (m)	0.032
b_{out} (m)	0.0029
D (m)	0.15
λ_{in} ($W*m-1K-1$)	0.42
λ_{out} ($W*m-1K-1$)	0.42
Σ (m)	0.04
B (m)	8.00

4. Results of the sensitivity analysis

The results of the sensitivity analysis consist of 108 numerical simulations, for which Table 3 summarises the main results.

From a general point of view, a highly permeable medium in transient groundwater conditions behaves in a very different way with respect to the other lithologies. For fractured limestones and sands with transient groundwater, the higher the flow rate of the heat transfer fluid is, the higher the heat power extraction is. According to this, the higher the thermal conductivity of grouts, the greater the heat power extraction is.

Even if a distinct behaviour between the three investigated lithologies persists, the difference in heat power extraction decreases when the groundwater is moving at a negligible velocity. Moreover, in dry groundwater conditions other factors come into play: this is more pronounced in sand deposits where increasing the flow rate of the heat transfer fluid greatly improves the heat power extraction, but results in higher pumping costs and energy consumptions could occur as highlighted by Zhu et al. (2019) and Badenes et al. (2020a).

A temperature variation of 5 °C with respect to the undisturbed ground temperature (T = 14 °C) was considered an acceptable thermal disturbance, avoiding environmental issues throughout and around each studied BHE during the plant operation. This was reflected both in the longitudinal (Y-axis) and transverse (X-axis) directions referring to the groundwater flow (Figure 2): the differences are more pronounced along the longitudinal direction, especially when transient groundwater conditions occur.

A more elongated thermal plume along the longitudinal direction that spreads until it is more than 15 m from BHE is clearly noticeable for porous lithologies such as sands, while it decreases for more conductive but less porous lithologies such as limestones. In this case, an oval-shaped thermal plume elongated until more than 10 m was displayed, which was when transient groundwater conditions occurred?

Although less evident, both sands and limestones show a slight increase in thermal dispersion with increasing flow rates and grout thermal conductivities, under both steady state and dry groundwater conditions. This displays thermal plumes with more circular shapes and records any valuable change.

In contrast, the lowest porous and conductive lithologies such as clayey silts do not show any meaningful variation, so the thermal plume is kept constant with a circular shape (until greater than 3 m) for all the investigated situations.

Moreover, the undisturbed ground temperature along the transverse directions with respect to the groundwater flow is achieved not farther than 5 m from BHEs for all the considered case studies.

5. Discussion

The investigation of 4 grouts with increasing thermal conductivities coupled to 3 different hydrogeological situations, highlights how transient groundwater conditions allow for obtaining the lowest thermal disturbance in the ground around the BHE, compared to steady-state groundwater conditions.

The study confirms how lithological properties play a key role in handling BHE performance and can be greatly enhanced by optimizing

Table 3. Main outputs from the simulations. Keys: T_{out} (°C) is the outflow temperatures; ΔT (°C) is the difference between T_{in} and T_{out}; P is the Power (W/m); D, WS and WT corresponds to Dry, Steady state and Transient groundwater conditions (20, 40, and 60 refers to the distinct flow rates inside the pipes, in m^3/d); G1, G2, G3, G4 are the grouts, respectively with λ of 0.5, 1.0, 1.5 and 2.0 W $m^{-1}K^{-1}$.

		Limestone			Sand			Clay/Silt		
		T out (°C)	ΔT (°C)	P (W/m)	T out (°C)	ΔT (°C)	P (W/m)	T out (°C)	ΔT (°C)	P (W/m)
D20	G1	5.20	1.20	11.55	4.91	0.91	8.76	4.61	0.60	5.78
	G2	5.34	1.34	12.90	5.00	1.00	9.63	4.64	0.63	6.07
	G3	5.43	1.43	13.77	5.04	1.04	10.01	4.65	0.64	6.16
	G4	5.40	1.40	13.48	5.08	1.08	10.40	4.67	0.65	6.26
D40	G1	4.66	0.66	12.71	4.45	0.45	8.67	4.31	0.35	6.74
	G2	4.76	0.76	14.63	4.54	0.56	10.40	4.33	0.36	6.93
	G3	4.81	0.81	15.60	4.56	0.57	10.78	4.34	0.37	7.12
	G4	4.85	0.85	16.37	4.58	0.58	11.17	4.35	0.38	7.32
D60	G1	4.45	0.45	13.00	4.33	0.33	9.53	4.21	0.21	6.07
	G2	4.52	0.52	15.02	4.37	0.37	10.69	4.22	0.22	6.35
	G3	4.55	0.55	15.89	4.38	0.38	10.98	4.23	0.23	6.64
	G4	4.58	0.58	16.75	4.40	0.40	11.55	4.24	0.24	6.93
WS20	G1	5.20	1.20	11.55	4.90	0.90	8.67	4.60	0.60	5.78
	G2	5.36	1.36	13.09	5.00	1.00	9.63	4.63	0.63	6.07
	G3	5.43	1.43	13.77	5.03	1.03	9.92	4.65	0.65	6.26
	G4	5.50	1.50	14.44	5.07	1.00	10.30	4.67	0.67	6.45
WS40	G1	4.66	0.66	12.71	4.49	0.49	9.44	4.31	0.31	5.97
	G2	4.76	0.76	14.63	4.54	0.54	10.40	4.33	0.33	6.35
	G3	4.81	0.81	15.60	4.56	0.56	10.78	4.34	0.34	6.55
	G4	4.85	0.85	16.37	4.59	0.59	11.36	4.35	0.35	6.74
WS60	G1	4.45	0.45	13.00	4.33	0.33	9.53	4.21	0.21	6.07
	G2	4.51	0.51	14.73	4.37	0.37	10.69	4.23	0.23	6.64
	G3	4.55	0.55	15.89	4.38	0.38	10.98	4.23	0.23	6.64
	G4	4.58	0.58	16.75	4.40	0.40	11.55	4.24	0.24	6.93
WT20	G1	5.72	1.72	16.56	6.72	2.72	26.19	4.62	0.62	5.97
	G2	6.09	2.09	20.12	7.87	3.87	37.26	4.66	0.66	6.35
	G3	6.26	2.26	21.76	8.49	4.49	43.23	4.67	0.87	6.45
	G4	6.42	2.42	23.30	8.89	4.89	47.08	4.70	0.91	6.74
WT40	G1	4.99	0.99	19.06	5.71	1.71	32.93	4.33	0.33	6.35
	G2	5.26	1.26	24.26	6.76	2.76	53.15	4.35	0.66	6.74
	G3	5.38	1.38	26.57	7.44	3.44	66.24	4.35	0.67	6.74
	G4	5.50	1.50	28.88	7.94	3.94	75.87	4.37	0.70	7.12
WT60	G1	4.68	0.68	19.64	5.57	1.57	45.35	4.22	0.22	6.35
	G2	4.87	0.87	25.13	6.32	2.32	67.01	4.23	0.23	6.64
	G3	4.96	0.96	27.73	6.95	2.95	85.21	4.24	0.24	6.93
	G4	5.05	1.05	30.33	7.48	3.48	100.51	4.25	0.25	7.22

the thermal properties of pipes and grout materials, as demonstrated by Giordano et al. (2019), Smith and Elmore (2019), and Badenes et al. (2020b). According to many authors (Wang et al., 2009; Casasso and Sethi, 2014; Van de Ven et al., 2021; Chen et al., 2022), during transient groundwater conditions the advection process is verified, and the BHE performance greatly improves. Therefore, with and without a steady state groundwater flow, the worst condition due to the higher impact in increasing the thermal disturbance of the ground around the BHE is verified. Additionally, increasing the flow rate of the heat transfer fluids through pipes further contributes to achieving the lowest thermal disturbance heavily affecting the BHE performance (Casasso and Sethi, 2014; Chen et al., 2022), especially when transient groundwater conditions occur, which can significantly affect the final heat power extraction (Pan et al., 2020).

The obtained results revealed that more porous and more conductive lithologies, such as sands and limestones respectively, exhibit very different increases in terms of the thermal conductivity of the grout as well as the flow rate of the heat transfer fluid. On the other hand, less conductive and less porous grounds display negligible differences.

A further comparison with different groundwater conditions was performed: when steady state and dry groundwater conditions occur, more porous and more conductive lithologies behave exactly in the opposite way than in the transient modality. Groundwater moving throughout pores at certain velocities can indeed contribute to notably increasing the thermal properties from dry to wet conditions (Chicco et al., 2019), leading to a proper exchange and a convective thermal balance with the heat transfer fluid.

Figure 3 shows the ending outlet temperatures (T_{out}) of the heat transfer fluid when high flow rates (60 m^3/d) and transient groundwater conditions occur.

In general, after a few days of plant functionality the heating cycles stabilise for limestones and clay/silts, mainly depending on the ground characteristics; for sands, the stability is reached in the first few hours and mainly depends on the grout thermal conductivity. Moreover, T_{out} curves behave differently: the use of lower to highly conductive grouts were revealed to be important for porous lithologies such as sands (T_{out} curves show different values after one month of plant functionality), while it is not relevant for less porous and less conductive soils such as clay/silts, where a unique value is reached after 30 days.

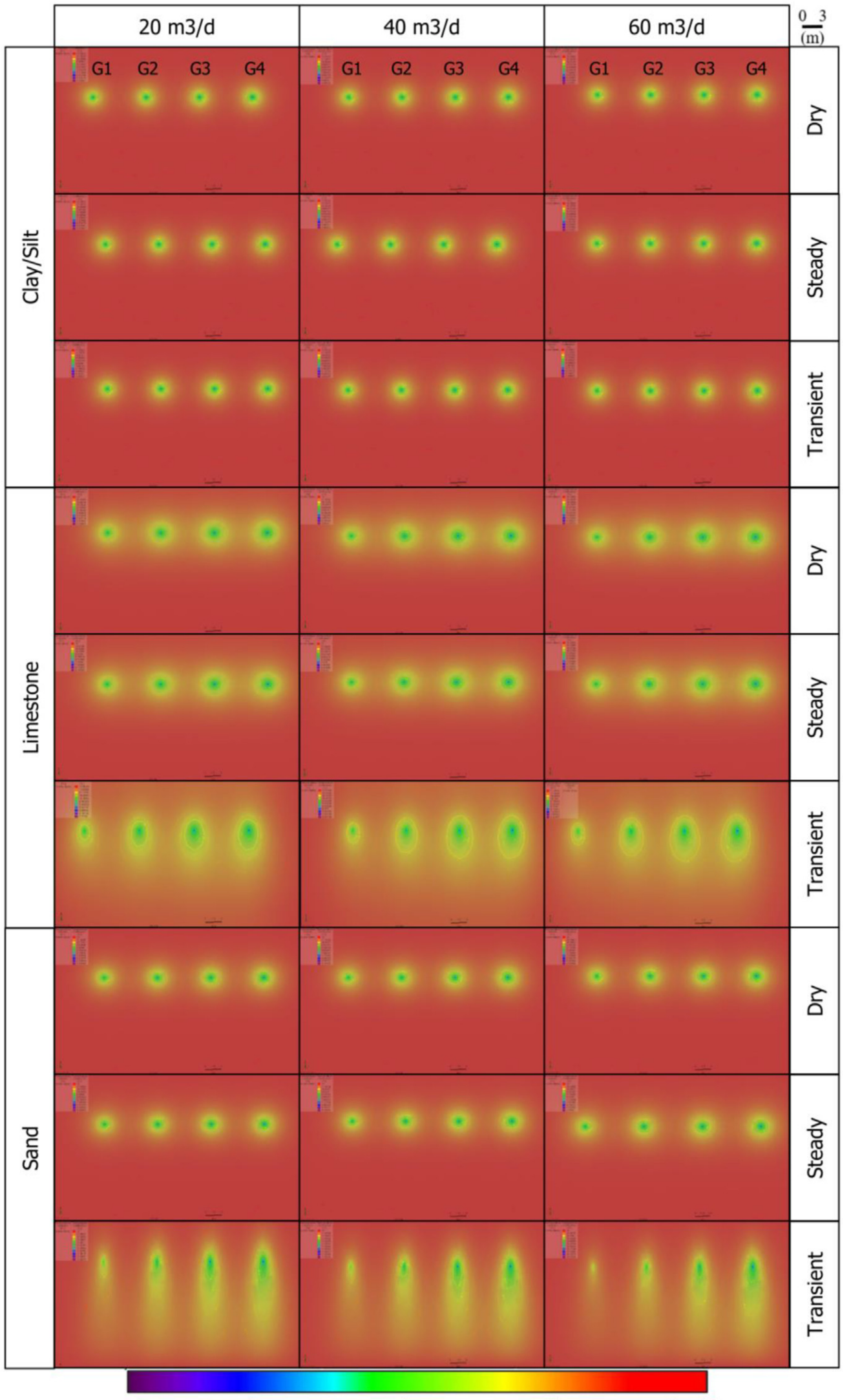

Figure 2. Thermal perturbation around BHE at -60 m depth from the ground in clayey silt, limestone and sand lithologies: three groundwater conditions (dry, steady and transient), with different pipes discharges (20, 40, 60 m^3/d) are considered, comparing with four kinds of grout with a distinct thermal conductivity (G1 = 0.5, G2 = 1.0, G3 = 1.5 and G4 = 2.0 W $m^{-1}K^{-1}$). At the bottom, the colour bar represents lower (blue) to higher (red) temperature values.

Based on different groundwater and geological conditions, the heat extraction difference (%) with respect to the less performant grout (G1 = 0.5 W $m^{-1}K^{-1}$) using an average flow rate of 40 m^3/d, is shown in Figure 4. When groundwater is present, the ground greatly increases its potentiality and an efficient grout can substantially improve the production. This is very pronounced for more porous lithologies such as sands, and to a lesser extent for more conductive lithologies such as limestones. In contrast, when facing low porous and low conductive lithologies (clay/silts), the use of different grouts under different groundwater conditions does not affect the heat power extraction. As a general remark, a good grout can improve the heat extraction by at least 10%.

Using the same ground and groundwater conditions, the heat extraction difference between low and high flow rates (% with respect to the lower flow rate), is also considered. Using high flow rates in more porous grounds and with transient groundwater conditions, greatly improves the heat extraction while it was negligible in clay/silts lithologies

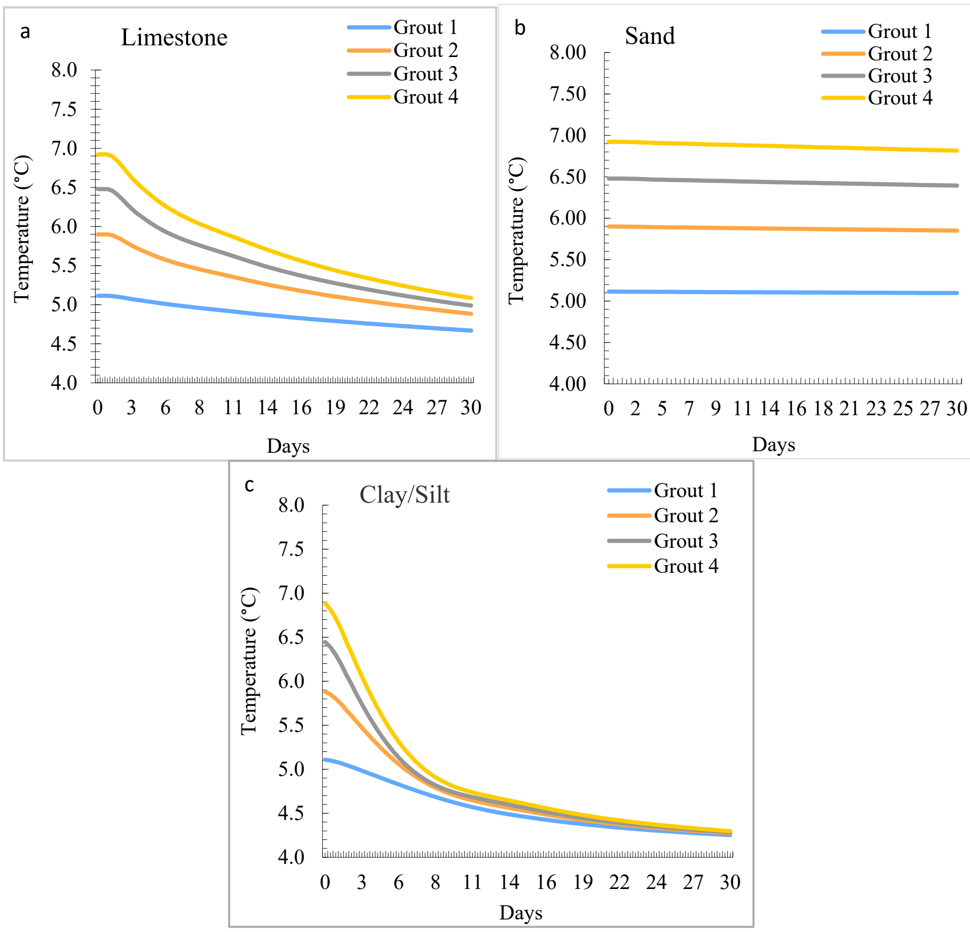

Figure 3. Outlet temperatures (T_{out}, °C), after 30 days of plant operation for 3 kinds of ground (Limestone in a; Sand in b; Clay/Silt in c). Transient groundwater conditions and flow rate at 60 m^3/d, are set; different grouts at increasing thermal conductivity, are compared.

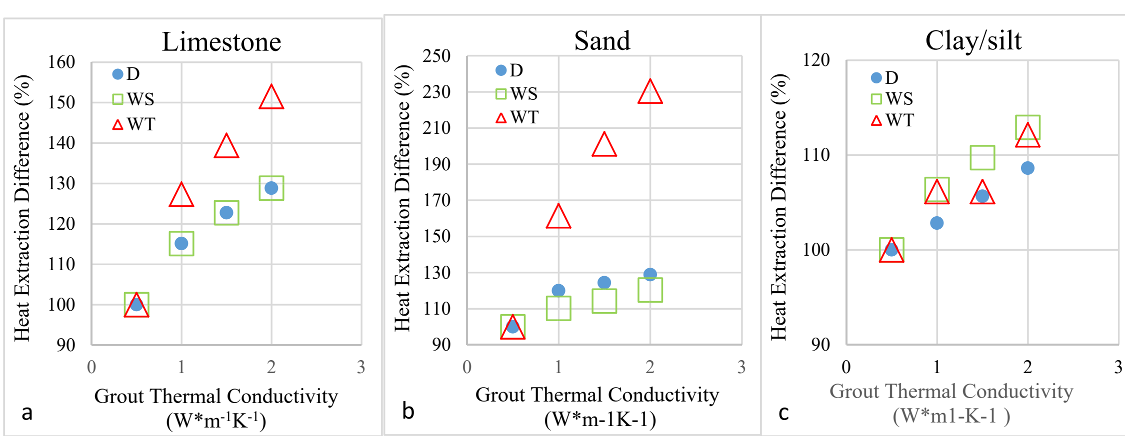

Figure 4. Differences in heat power extraction (% with respect to G1 at 40 m^3/d) comparing the four analysed grouts, in different geological (Limestone in a; Sand in b; Clay/Silt in c) and groundwater conditions (D = dry, WS = steady state, WT = transient).

(Figure 5). Although to a lesser extent, a similar situation is also recorded for more conductive lithologies, such as limestone, where the use of higher flow rates (40 and 60 m^3/d) is fundamental for improving heat extraction.

The obtained results are in agreement with Erol (2011), where the use of high to low conductive grouts over different groundwater conditions, was shown. Investigating different groundwater conditions such as dry, steady state and transient groundwater conditions, can better detail the heat transfer giving more accurate heat extraction values. For instance, the differences between dry to steady state groundwater situations are negligible and thus the change in some operative parameters such as grout or flow rate, does not affect the overall BHE performance. These almost equal values could be explained because in both cases the heat conduction is predominant, while when the groundwater moves with a certain velocity advection component occurs and the heat extraction increases considerably in terms of its potentiality.

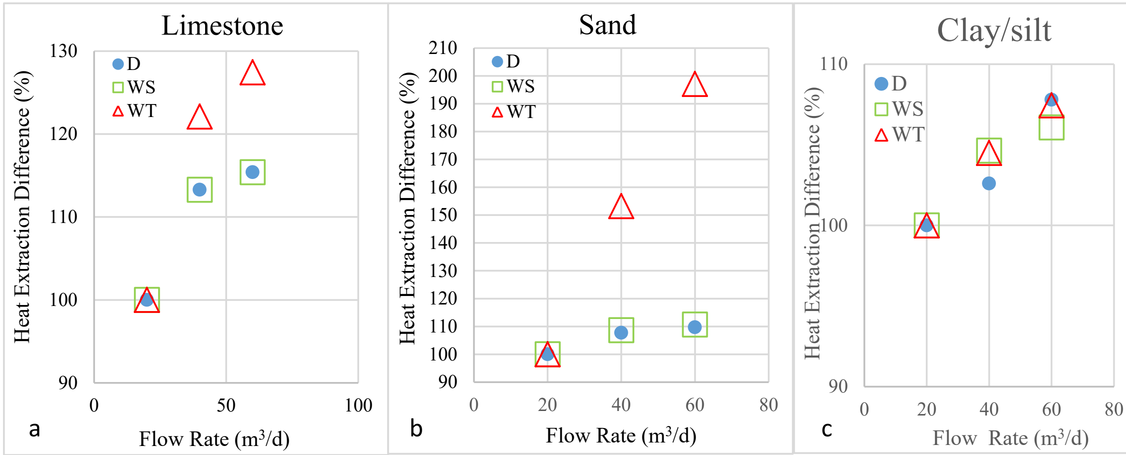

Figure 5. Differences in heat power extraction (% with respect 20 m^3/d and using G3) comparing three increasing flow rates, in different geological (Limestone in a; Sand in b; Clay/Silt in c) and groundwater conditions (D = dry, WS = steady state, WT = transient).

6. Conclusions

Knowledge of the correct amount of heat to be obtained from specific hydrogeological contexts has proved to be of great relevance in optimizing the energy transfer, and hence in decreasing environmental impacts as well as the overall costs of the plant.

The study highlighted that the use of low to high thermal conductive grouts is not relevant for less porous or poorly conductive lithologies such as clayey silt deposits. In this case, T_{out}-T_{in} does not overcome a difference of 0.2% if the flow rate of the heat transfer fluid increases, and with transient groundwater conditions.

In contrast, more conductive limestone and highly porous sands behave differently: in these cases, the BHE performance can be improved a using a higher conductive grout. This increase can be further reached if the flow rate of the heat transfers fluid increases and when the groundwater moves at high velocities increasing the convective heat transfer. In these cases, T_{out}-T_{in} can reach values of approximately 16% for limestones and up to 43% for sands, highlighting how the use of a high conductive grout is of great relevance in improving BHE performances with this ground.

In summary, transient groundwater conditions reveal the most suitable condition for obtaining a high efficiency of BHE and of the entire GSHP plant. It increases much more in conductive grounds and with higher conductive grouts as well as higher flow rates of the heat transfer fluid. This confirms that conductive and convective components of the heat transfer are predominant and hence, must be properly defined. On the other hand, in the case of poorly conductive ground the influence of grouting is negligible, and it is not worth investing in high-performance materials since the system does not particularly benefit from it.

This research highlighted how the change in some design conditions, such as low to high conductive grouts and flow rates of the heat transfer fluid, may enhance the final heat power extraction especially when specific lithologies and groundwater conditions occur.

In conclusion, the use of more performing grout and higher flow rates through pipes can reveal important parameters to be taken into account in enhancing heat extraction, especially when facing to porous lithologies and transient groundwater conditions.

Declarations

Author contribution statement

Jessica Maria Chicco, Giuseppe Mandrone: Conceived and designed experiments; Performed the experiments; Analyzed and interpreted data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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