Quantifying the effect of single fractures on the thermal performance of borehole heat exchangers

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Keywords: borehole heat exchanger, groundwater, fracture, aquifer, thermal transport, ground source heat.

ABSTRACT

Ground-source heat pump schemes for space conditioning and thermal storage increasingly use vertical borehole heat exchangers (VBHEs). Current models for VBHE performance often assume homogeneous ground conditions and the absence of flowing groundwater. However, in reality, the ground, especially bedrock, is commonly fractured. In this paper, numerical analysis is used to investigate a range of scenarios in which an open fracture with flowing groundwater may influence the thermal performance of a VBHE. It is intuitive to think that flowing groundwater always increases the heat transfer to and from a VBHE and hence improves their efficiency by reducing the temperature at the borehole wall. However, the results presented in this paper demonstrate that the presence of a fracture within permeable strata can also reduce the performance of a VBHE by locally lowering groundwater flow velocities in the rock matrix. Therefore the influence of a nearby open fracture may either improve or worsen the VBHE thermal performance depending on the fracture orientation relative to the borehole, the regional hydraulic gradient and the ratio of hydraulic permeabilities of the matrix and the fracture.

1. INTRODUCTION

Vertical borehole heat exchangers (VBHEs) are among the most popular ground source heat pump designs because they can be installed in a wide range of geological conditions (Dehkordi et al 2015), require only a small ground area and cause minimal landscape disturbance (Yang et al 2010). Additionally, no licensing for groundwater abstraction or injection is required because it is a closed-loop system. Future use of GSHP systems (including VBHE) is set to increase as the market for low-carbon technologies grows (Carvalho et al 2015). Improved energy efficiency for buildings is required by EU legislation (Directives: 2010/31/EU (EU Council 2010c), 2012/27/EU (EU Council 2012), 2009/125/EC (EU Council 2009), 2010/30/EU (EU Council 2010b), 2009/28/EC (EU Council 2010a)). Additionally, government authorities of EU member states provide financial support for the use of renewable energy sources for heating and cooling to reduce primary energy dependency and greenhouse gas emissions (Cansino et al 2011).

Consideration of groundwater effects on VBHE can significantly change the estimated thermal performance and interactions of VBHE systems, especially in congested urban environments. Capozza et al (2013) quantified the value of considering groundwater flow during VBHE design, and concluded it saved 16% on the project investment costs. Ferguson (2015) points out that if groundwater velocity exceeds 1×10^{-8} m/s (8.6×10^{-4} m/day) then it should be accounted for during modelling of VBHE, because it increases the apparent thermal conductivity (ATC) of the ground, as defined by Sauty et al (1982). Therefore, the effectiveness of thermal exchange can be significantly increased by the groundwater flow. Groundwater flow also reduces the time taken to reach steady state (Tye-Gingras and Gosselin 2014; Rivera et al 2015).

However, hydrogeological conditions are rarely simple and homogeneous. The influence of groundwater is frequently ignored and practical guidelines are lacking (Tye-Gingras and Gosselin 2014). Modelling of VBHE thermal performance is an effective tool to estimate the time to reach steady state and whether the system will be profitable over the whole life-cycle (Retkowski et al 2015). Currently used models of VBHEs that account for groundwater flow often assume homogeneous ground conditions. The moving infinite line source model (MILS) (Carslaw and Jaeger 1959) is a 2D analytical model to account for the influence of groundwater on the VBHE thermal balance. It accounts for groundwater advection and radial conduction and assumes a VBHE installed in a homogenous aquifer. This model was modified by Metzger et al (2004) to account for 2D thermal dispersion. However, in practice, VBHEs are frequently installed in heterogeneous and fractured media which may have groundwater flow (Dehkordi et al 2015). Use of the averaged thermal properties in a layered or heterogeneously fractured aquifers to estimate the thermal performance of VBHE can give significantly erroneous results concerning the thermal performance of VBHE (Loveridge et al 2013; Erol 2016).

Recent research has investigated the effect of fractured aquifers on VBHE thermal performance. Several studies modelled the influence of a single open fracture set in a 'matrix' of low hydraulic conductivity material. In these cases, the fracture increases the apparent thermal conductivity of the ground, thereby improving the estimated thermal performance of VBHE and exacerbating downstream thermal impacts (Gehlin and Hellström 2003; Liebel et al 2012; Dehkordi et al 2015), even if the flow rate of groundwater in such a fracture is low. However, studies investigating the performance of VBHE nearby a flowing fracture under different hydrogeological conditions are few. Thus, there is a need for systematic analysis and quantification of the effects of open fractures on the long-term thermal performance of VBHEs for a wide range of hydrogeological conditions, including considerable groundwater flow in the matrix.

This study uses 2D numerical modelling to investigate a range of possible hydrogeological scenarios in which an open, flowing fracture may influence the long-term thermal performance of VBHEs. The key question considered by this study is: when does an open fracture improve (and when does it worsen) the thermal performance of a VBHE, compared with the thermal performance estimated assuming a homogenous host rock?

2. METHODS

A 2D (in plan) finite element analysis is used to assess the effect of a single vertical fracture on the thermal behaviour of a single VBHE installed within a permeable rock matrix. Conceptualisation of the model is shown in Figure 1. The model has a circular domain of 400 m radius and has two variants, one with a fracture and one without. These variants are described in Section 2.5. A range of scenarios were investigated for the case with an open fracture based on changes to some of the key parameters which are shown on Figure 1 and identified below:

- D_f – fracture distance from the VBHE wall perpendicular to fracture line;
- S_f – fracture shift from its mid-length, longitudinal to fracture orientation, positive (+) in the direction of groundwater flow;
- $H(x)$ – fixed hydraulic head at domain boundary.

The following subsections describe the key model attributes.

2.1 Assumptions

The analyses assume that:

- There is local thermal equilibrium between the aquifer solid and water.
- Thermal expansion is neglected.
- Material and fluid properties are constant with temperature.
- The porous material of the aquifer, referred to as the 'matrix', is homogeneous, isotropic and saturated.
- Dispersivity of heat in the matrix is assumed to be negligible.
- Dispersivity of heat in the fracture is ignored as advection is the key heat transfer process inside it (COMSOL 5.2a 2016).
- All water in the matrix is mobile.
- The fracture is a vertical plane (represented as a line in the 2D model); it is a saturated porous medium with distinct hydraulic and thermal properties.
- Fluid flow is laminar and described by Darcy's law (Bear 1988).
- Heat is transferred by conduction and advection.
- The study does not investigate the effects of closed fractures that may act as hydraulic barriers.

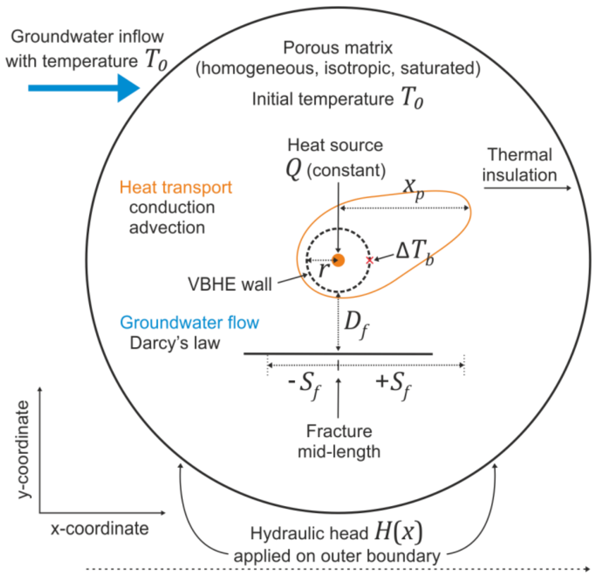


Figure 1 Conceptualisation of the TAF numerical model. Not to scale. The red cross identifies the location of the measurement of temperature change at VBHE wall, ΔT_b. The orange line shows an example of the generated thermal plume of length X_p.

2.2 Model physics

Steady-state Darcian flow is assumed in the matrix. Initial values of hydraulic head, H, for the model domain and hydraulic head boundary condition on the domain outer border were set using the x coordinate and a constant hydraulic gradient in the x direction:

$$\mathrm{H}(x) = -Mx \qquad [1]$$

where M is the constant hydraulic gradient in the x direction (-), which is valid when the matrix is homogenous, i.e. when there is no fracture in the matrix.

The effect of a fracture on the VBHE was examined for two different groundwater flow rates, v_∞ (0.05 m/day and 0.0005 m/day); v_∞ is defined as the 'undisturbed' Darcy velocity that would occur in the matrix in the absence of a fracture.

The value of matrix hydraulic conductivity K_m (m/day) was set as

$$K_m = -v_\infty / M \qquad [2]$$

The fracture is coupled to the matrix by continuity of hydraulic head and by conservation of flow into and from the fracture. Steady state water flow in the fracture is modelled along a line. The fracture is represented as a straight linear object with the fracture aperture represented as a property of the line. Flow in fracture is modelled parallel to the interior boundary (line) representing the fracture within a matrix.

The hydraulic conductivity of the fracture, K_f, is defined in relation to the hydraulic conductivity of the matrix as

$$K_f = K_m R_K \qquad [3]$$

where R_K is the ratio of the hydraulic conductivity of the fracture to that of the matrix (dimensionless).

Heat transfer is modelled by conduction (Fourier's law) and by convection with the fluid flow.

The effective conductivity of the solid-fluid system for the matrix and the fracture is calculated as the weighted arithmetic mean of the thermal conductivities of mobile water and solid material, i.e. the volume average. This volume average model provides an upper bound to the effective thermal conductivity. This method was selected because heat conduction occurs in parallel in the solid and the fluid. The effective conductivity of solid-fluid system in the fracture was calculated excluding dispersive heat transport.

An 'open' boundary condition was applied to the outer domain, allowing heat to advect into the domain carried by water at a specified arbitrary reference zero exterior temperature (T_0 = 273.15 K, 0°C) with the inflow. The outer boundary was otherwise assumed to have zero conductive heat-flux across it (eq. [4]).

$$\begin{aligned} T &= T_o\,,\ \text{if}\, \boldsymbol{n}\cdot\boldsymbol{v} < 0 \\ -\boldsymbol{n}\cdot\boldsymbol{q} &= 0\,,\ \text{if}\, \boldsymbol{n}\cdot\boldsymbol{v} \geq 0 \end{aligned} \qquad [4]$$

where $\boldsymbol{n}$ is the outward normal vector of the boundary (dimensionless), $\boldsymbol{v}$ is Darcy's velocity vector (m/day) and $\boldsymbol{q}$ is the conductive heat flux vector (W m^{-2}).

2.3 Boundary conditions

Zero conductive flow is assumed over the outer model boundary. Therefore the outer boundary is thermally insulated because the model size is large enough, for heat not to reach the model boundary. The hydraulic head on the domain boundary is fixed. In every simulation a check was made to ensure that the simulated velocities were low enough to maintain laminar flow. In only the few simulations were the groundwater velocities are such that the Reynolds numbers exceeded 10, these were excluded from the analysis.

2.4 Heat source

The heat source, Q, delivers a constant power (heat injection) and was represented as a circular heated domain with a small radius (2 cm). This was done both for simplicity and to aid validation of the model against the MILS analytical solution where the VBHE is approximated as a point source (Sutton et al 2003; Diao et al 2004). The heat source was installed inside the circular domain of radius 5 cm, which represents the grout of the VBHE (Figure 1). The VBHE has a radius of 5 cm, and therefore the temperature probe was located on the borehole wall downstream at x, y = [5, 0] cm. This point, ΔT_b, is marked by a red circle in Figure 1. The VBHE grout and heat source are impermeable and have typical grout material properties (Table 1). There is no seasonal variation in VBHE operation.

2.5 Hydrogeological scenarios

The numerical model has two variants:

1. **TAF** –**T**hermal transport from a VBHE through an **A**quifer in the presence of a single vertical **F**racture.
2. **TAH** –**T**hermal transport through **A**quifer with **H**omogenous matrix. It differs from TAF only in the aquifer being homogenous, i.e. the fracture is absent. The moving infinite line source (MILS) analytical solution (Carslaw and Jaeger 1959; Stauffer et al 2014) was used to optimise the mesh and for spatial and temporal validation of the TAH model.

A range of scenarios were investigated, to examine how an open fracture may influence the thermal performance of a VBHE. The fixed model parameters are shown in Table 1. In the single parameter analysis, the numerical model was run with individual fracture parameters changed for each model run and the remaining parameters fixed to the base values, given in Table 2. The results of a systematic single-parameter sensitivity analysis are discussed with reference to the fracture distance relative to the VBHE (D_f) measured perpendicular to fracture line. Additionally, the single-parameter sensitivity analysis was carried out for the fracture shift, (S_f) that is measured along the orientation of a fracture (along the x coordinate) from the point at fracture mid-length (Figure 1). Fracture shift is positive if the shift is in the positive direction of x coordinate (downstream for groundwater flow). In all simulations, the fracture was parallel to the groundwater flow direction.

The single-parameter sensitivity analysis was done for two groundwater flows in the matrix (v_∞) of 0.005 m/day (slow) and 0.05 m/day (medium). Fracture parameters for the single-parameter sensitivity analysis were selected from initial manual trials so as to significantly influence the temperature change and plume extent from the VBHE. The fracture thickness was selected to be "moderately wide" (i.e. 0.005 m) based on the classification of fractures by openness (ISRM 1978). Parameter values are given in Table 1 and Table 2. The selected fracture length (50 m) is based on the fracture length distributions found by Hardebol et al (2015) from investigation of the size distributions of fractures in a carbonate platform from Dolomites, Italy. The base value for fracture shift S_f was 0 m, i.e. the fracture was centred relative to VBHE.

2.6 Parameters and material properties

The time interval of the model runs from 10^{-3} days (86.4 seconds) to 300 years, divided logarithmically into 128 time steps. All fixed parameters are given in Table 1. Thermal properties for the aquifer matrix material (density, effective volumetric heat capacity and effective thermal conductivity) were set based on typical sandstone values (Stauffer et al 2014). The matrix hydraulic conductivity, K_m, was based on a target groundwater velocity in a homogenous matrix (v_∞) and a constant hydraulic gradient, M, in the x direction (for a homogenous matrix). This allowed the model to be run for specified groundwater velocities in an undisturbed matrix, v_∞.

3. RESULTS AND DISCUSSION

3.1 Presentation format of the results

The results are presented in terms of the thermal performance of the VBHE, and also in terms of the extent of the downstream thermal plume. The thermal performance of the VBHE was measured as the temperature change at borehole wall (ΔT_b) after 30 years of continuous VBHE operation. ΔT_b was measured on the downstream side of the VBHE (i.e. at x = 0.05 m, y = 0 m). An additional performance criterion was the time for the borehole wall temperature to reach steady state. The plume extent was measured as the x-coordinate of thermal plume, also after 30 years of continuous operation. The thermal plume of interest was selected to be for 2K temperature change (X_{2K}). If a fracture is present, the maximum plume extent may have a non-zero y-coordinate. These criteria were estimated for each set of fracture parameters and for different groundwater flows in undisturbed aquifer matrix. Results were compared with the thermal performance of VBHE for a homogenous aquifer (i.e. in a matrix without a fracture, TAH). In the results that follow, relative performance factors (R, eq. [5]) are reported, i.e. the difference between the TAF and TAH models.

$$R = \frac{X_{TAF} - X_{TAH}}{X_{TAH}} \qquad [5]$$

where X is the parameter of interest, for example the temperature at the borehole wall, and the subscripts represent the model variant. The results of the single-parameter analysis are presented for varying fracture distance (D_f) and shift (S_f) relative to the VBHE, while all other fracture parameters were kept fixed. The single-parameter analysis was carried out for two groundwater flows in an undisturbed matrix (v_∞), 0.005 m/day (slow) and 0.05 m/day (medium). All fixed and varying fracture parameters are described in Table 2.

3.2 Results of single-parameter analysis for fracture distance from VBHE

Figure 2 shows single-parameter analysis for fracture distance (D_f) from VBHE where relative performance factors are temperature change at VBHE wall after 30 years of continuous operation, ΔT_b (Figure 2 A) and time to stabilise it, t_{sb} (Figure 2 B).

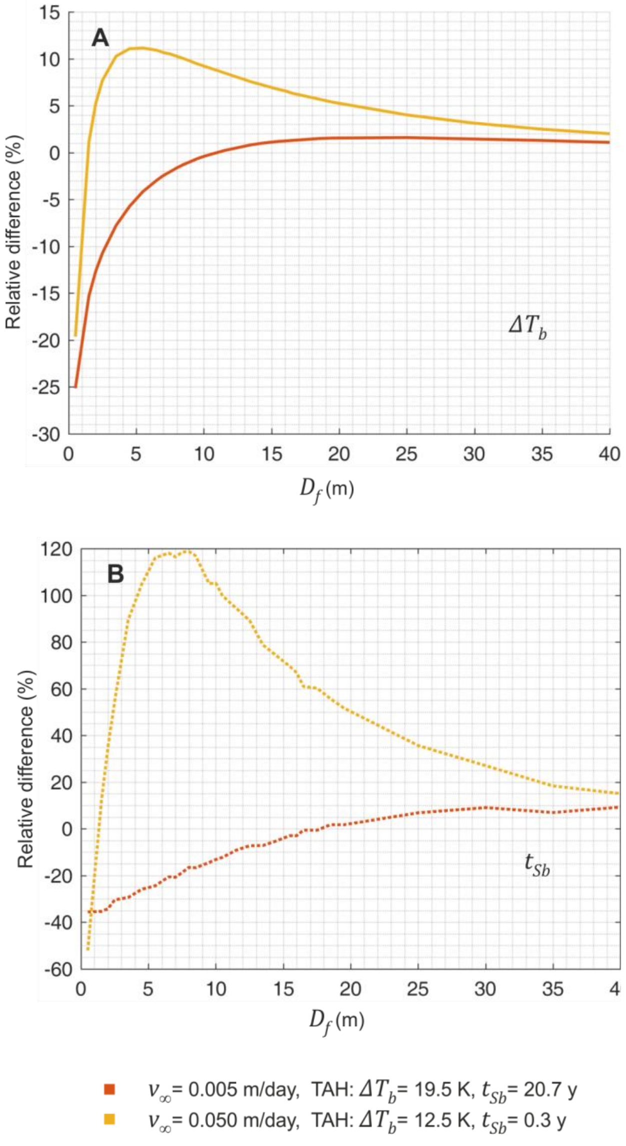


Figure 2 Relative difference (($\Delta T_{b\,\mathrm{TAF}}$ - $\Delta T_{b\,\mathrm{TAH}}$) / $\Delta T_{b\,\mathrm{TAH}}$) in: (A) modelled temperature change at VBHE wall, (ΔT_b) for 30 years of continuous operation; and (B) time to stabilise ΔT_b, (t_{sb}).

The results for slow groundwater flow in undisturbed matrix (v_∞ = 0.005 m/day) show that comparative to "absent fracture" scenario there is a considerable reduction in both ΔT_b and t_{sb} when fracture is close to VBHE (D_f = 0.5 to 10 m away). However, for D_f > 14 m ΔT_b is slightly higher for model scenario with fracture (TAF). This fracture effect diminishes as fracture is moved further away from VBHE (D_f > 30 m).

For scenario when v_∞ = 0.05 m/day fracture improves thermal performance of the VBHE (i.e. considerably reduces ΔT_b and t_{sb}) only for cases when fracture is located very close to VBHE (D_f < 1.5 m). In other cases, the presence of fracture worsens the thermal performance of VBHE (considerably increases ΔT_b and t_{sb}). The maximal increase in ΔT_b due to presence of fracture for tested scenarios is 1.4 K. However, fracture effect diminishes as fracture is moved further away from VBHE. The difference in the relative performance factors between TAH and TAF scenarios for ΔT_b and t_{sb} when D_f = 40 m are 2% and 3%, respectively.

Figure 3 shows single-parameter analysis for fracture distance (D_f) from VBHE where relative performance factor is the maximal x-coordinate for the isotherm of +2 K temperature change (X_{2K}) for 30 years of continuous VBHE operation. The results for slow groundwater flow in undisturbed matrix (v_∞ = 0.005 m/day) show that comparative to "absent fracture" scenario X_{2K} is increased when fracture is close to VBHE (D_f < 5 m).

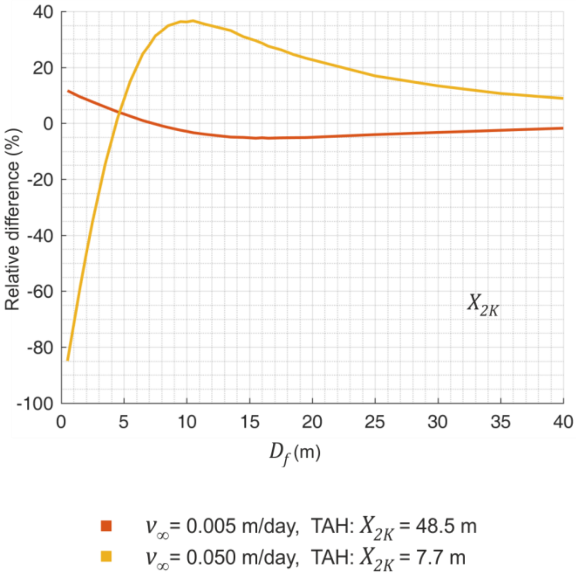


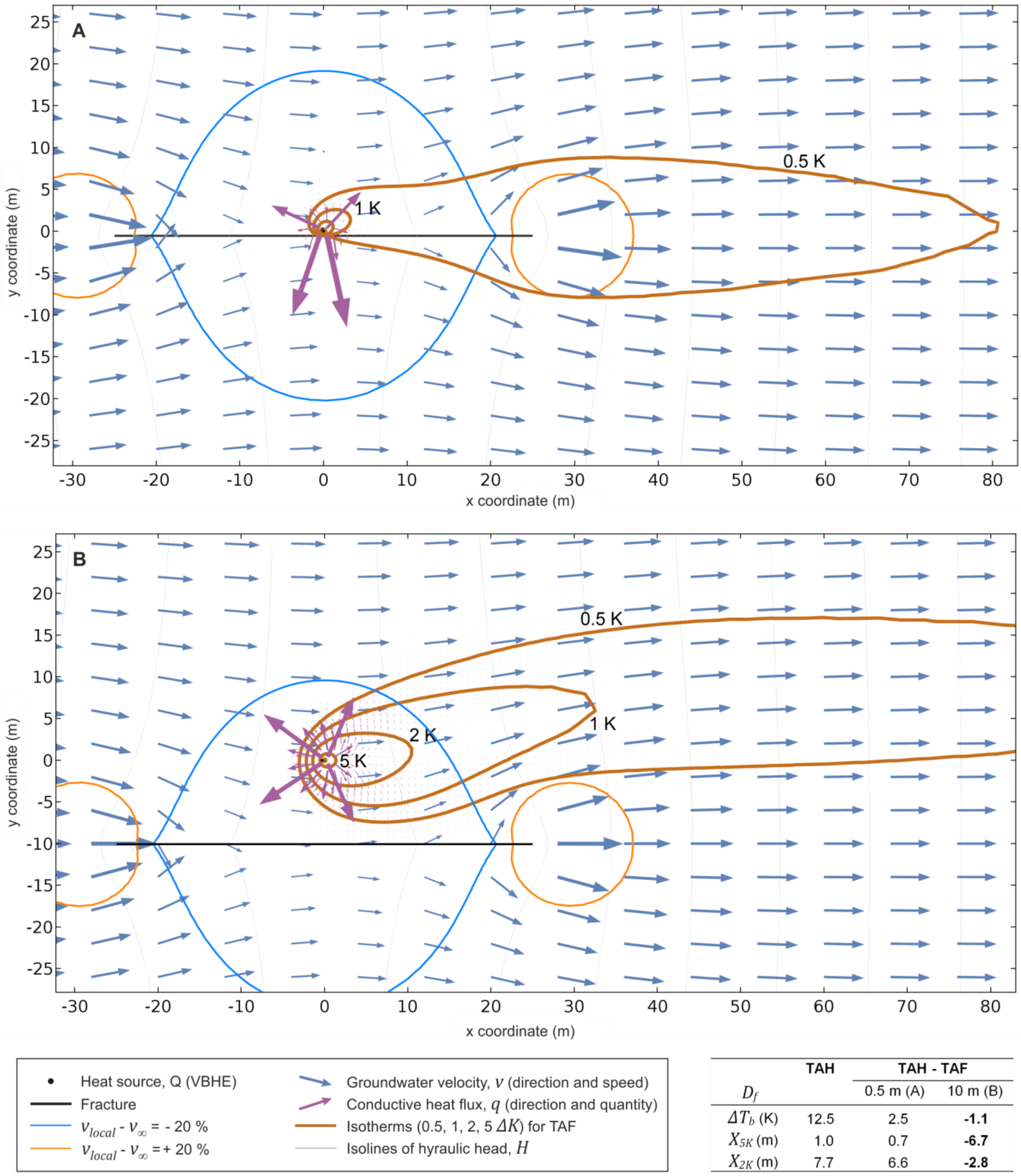
Figure 3 Relative difference (($\Delta T_{b\,\mathrm{TAF}}$ - $\Delta T_{b\,\mathrm{TAH}}$) / $\Delta T_{b\,\mathrm{TAH}}$) in the modelled maximal x-coordinate of the thermal plume of 2K temperature, X_{2K} for 30 years of continuous VBHE operation.

For scenario when v_∞ = 0.05 m/day fracture significantly reduces X_{2K} comparing to "absent fracture" scenario for D_f < 4 m. However, for cases when D_f > 4 m the presence of fracture significantly increases X_{2K}. The maximal increase in X_{2K} due to presence of fracture for tested scenarios with v_∞ = 0.05 m/day is about 3 m. However, fracture effect diminishes as fracture is moved further away from VBHE (D_f > 35 m, Figure 3). Note that slow groundwater flow in matrix (0.005 m/day) causes longer thermal plume X_{2K} from VBHE and therefore presented relative changes in plume extent X_{2K} due to fracture effects comparing to TAH result ("absent fracture" scenario) are not as significant as for the case with medium groundwater flow in matrix (0.05 m/day).

3.3 Case studies to explain the effects of fracture distance on the VBHE

Two case studies are used to explain the effects of fracture distance on the thermal performance of VBHE. Both cases have medium groundwater flow in the undisturbed matrix (0.05 m/day). In the first case the fracture is close to VBHE (D_f = 0.5 m, Figure 4 A) and in the second case it is further away from the VBHE (D_f = 10 m, Figure 4 B). All other model parameters are kept constant.

A fracture that is closer to a VBHE (Figure 4 A) effectively increases heat transport from the VBHE. This significantly reduces the temperature at the borehole wall and reduces the spatial extent of the thermal plume of interest (see table enclosed in Figure 4). A fracture that is further away from the VBHE (Figure 4 B) affects mainly the local groundwater flow velocities near the VBHE; the thermal transport by the fracture is less marked. In these examples, where the VBHE was centred on the fracture mid-length, the presence of the fracture slowed down the groundwater velocities in the location of VBHE. This significantly increases the extent of small thermal plumes (i.e. +2 K and +5 K isotherms on Figure 4, which are small enough to be located in the affected area), as well as ΔT_b compared with the results for the "absent fracture" scenario (see Table enclosed in Figure 4). In conclusion, for medium groundwater flow (0.05 m/day), the dominant fracture effect can either be cooling of the VBHE (increased thermal transport) or a significantly slowing down of local groundwater velocities, thereby reducing the apparent thermal conductivity (ATC).



D_f	TAH	TAH - TAF	
		0.5 m (A)	10 m (B)
ΔT_b (K)	12.5	2.5	**-1.1**
X_{5K} (m)	1.0	0.7	**-6.7**
X_{2K} (m)	7.7	6.6	**-2.8**

Figure 4 Groundwater flow vectors and temperature contours for the thermal performance of a vertical borehole heat exchanger (VBHE) after 30 years of continuous operation installed near a vertical flowing fracture, where fracture distance (D_f) is 0.5 m (A) and 10 m (B) away from the VBHE. Groundwater flow in undisturbed matrix, v_∞ (far away from the fracture) is 0.05 m/day.

3.4 Systematic analysis of the effect of vertical fracture distance on the efficiency of the VBHE

The influence of fracture distance on the VBHE is first discussed for cases when the VBHE is centred with the fracture mid-length (S_f = 0 m). The fracture effects for these cases are shown in Figure 2 for ΔT_b and in Figure 3 for X_{2K} for medium (0.05 m/day) and slow (0.005 m/day) groundwater flow in matrix. Then the effects of fracture distance are discussed for cases when VBHE is not centred with fracture mid-length point, but rather it is shifted parallel to the fracture (S_f varies). This enables analysis of the effects of faster local groundwater velocities around the fracture edges on the thermal performance of the VBHE. The areas of the increased local groundwater velocities around fracture edges can be seen on examples by Figure 4.

3.4.1 Effects of fracture distance from VBHE in aquifer with medium groundwater flow

As was discussed in the case study (Figure 4), reduced Darcy's velocity due to fracture nearby the VBHE (which is located close to the fracture mid-length area) reduces the local ATC, and hence reduces thermal transport. The consequences for a matrix with medium groundwater flow (0.05 m/day) can be a significant increase in ΔT_b (Figure 2 A) and thermal plume length (X_{2K}, Figure 3) relative to the "absent fracture" scenario (TAH model). The other possible consequence is a significant increase in the time needed to stabilise ΔT_b (t_{Sb} in Figure 2 B), and, in a similar way, time to stabilise X_{2K}.

3.4.2 Effects of fracture distance from VBHE in aquifer with slow groundwater flow

When the matrix groundwater flow is slow (v_∞ = 0.005 m/day) the fracture does not significantly reduce the local groundwater velocities nearby VBHE compared with its undisturbed value. Thus, nearby fracture is beneficial to the VBHE installed in aquifer with slower groundwater flow, 0.005 m/day, and when fracture distance is small, D_f = 0.5 to 9 m (Figure 2 A).

For this case a fracture nearby VBHE is more beneficial for thermal performance of VBHE than for the cases with similar small D_f but with faster undisturbed groundwater flow in matrix (Figure 2 A). This is because a nearby fracture effectively increases thermal transport from the VBHE installed in a matrix with slower groundwater flow. Therefore in these cases, a nearby fracture significantly reduces ΔT_b and the time to stabilise it, t_{Sb}, compared with the homogenous case (TAH).

In a matrix with slow groundwater flow, a fracture that is further away from VBHE (12 m to 40 m away, Figure 2 A) also slightly increases ΔT_b (by only 0.3 K) comparing to TAH ("absent fracture" scenario). For these larger fracture distances, while the fracture is less effective in transporting heat from the VBHE, it is still able to reduce the local groundwater velocities in the area of the VBHE (for example, at D_f = 40m by about 5 % from the undisturbed value 0.005 m/day). If the fracture distance from the VBHE is increased further this effect becomes insignificant as well. In a matrix with slow groundwater flow, the effective fracture extends the maximal coordinate of the +2 K isotherm (X_{2K}) (Figure 3). This is because fracture effectively cools down VBHE wall but the volumetric flow in the fracture (in this tighter matrix) is not enough to reduce X_{2K} so this plume is advected downstream with the fracture, which effectively takes heat from the VBHE.

3.4.3 Effects of fracture location relative to VBHE

The location of fracture relative to the VBHE was changed by systematically varying the fracture shift (S_f) parallel to fracture orientation for two fracture distances from VBHE (1 and 5 m). The results for ΔT_b for VBHE installed in aquifers with medium and slow groundwater flow (Figure 5) can be explained by the interplay of two fracture effects on the ATC. Note that when S_f is increased beyond the fracture half-length, no line perpendicular to the fracture reaches the VBHE and the fracture has rapidly diminishing effect. Otherwise, the fracture can only increase the ATC local to VBHE compared with the TAH results when D_f = 1 m (Figure 5). Additionally, when there is medium groundwater flow in the matrix (0.05 m/day, Figure 5), the nearby fracture (D_f = 1 m) significantly accelerates the local groundwater flow around its edges, improving the thermal performance of the VBHE (reducing ΔT_b and X_{2K}) if it is located near the fracture edge (when S_f is around -25 m or +25 m, Figure 5).

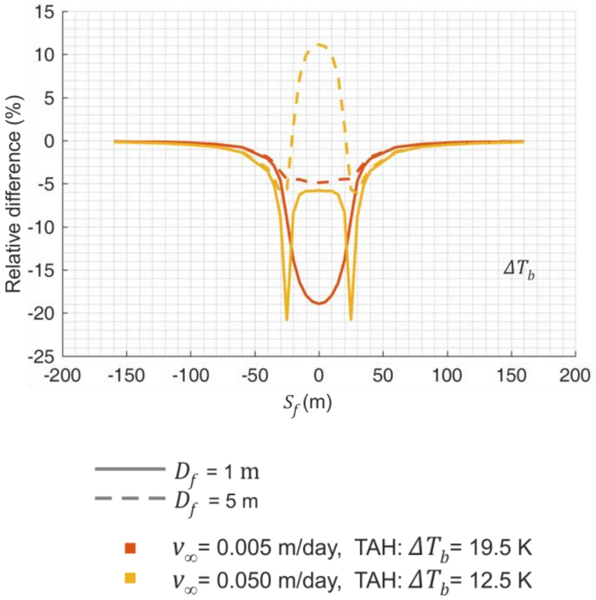


Figure 5 Relative difference (($\Delta T_{b\,\mathrm{TAF}}$ - $\Delta T_{b\,\mathrm{TAH}}$) / $\Delta T_{b\,\mathrm{TAH}}$) in temperature change at VBHE wall, ΔT_b after 30 years of continuous operation for varying fracture shift relative to the VBHE, S_f.

For all S_f, when D_f is kept at base value of 5 m, the fracture can either increase or reduce the ATC local to VBHE compared to a TAH ("absent fracture") scenario. This depends on the groundwater velocity in matrix (Figure 5). If the matrix has a medium groundwater velocity (0.05 m/day) the fracture effect on the VBHE is negative when it is located in the area of reduced local groundwater velocities (when S_f is between -20 m to +20 m, Figure 5).

In conclusion, a negative effect of a fracture on VBHE performance (increase in temperature change at VBHE wall, ΔT_b, compared to an “absent fracture” scenario) is much more significant for scenarios where matrix has medium groundwater velocity (0.05 m/day) than for matrix with slower groundwater flow. This is because in this case the fracture significantly changes nearby local groundwater velocities. For tested cases with medium groundwater flow in matrix, the open fracture nearby VBHE was able to increase ΔT_b by 1.4 K compared to “absent fracture” scenario where VBHE is installed in homogenous aquifer. This is because for medium matrix groundwater flow (0.05 m/day) the cooling effect of the fracture can be more than countered by the slowing of local matrix groundwater velocities, so the temperature change at the VBHE wall if it is located in the affected area can be significantly increased by the influence of fracture. Thermal plume can also be increased by fracture presence if it occupies area with reduced local groundwater velocities by fracture. When the negative effect of a fracture on VBHE performance is significant (i.e. when it is located in the area of significantly slowed groundwater velocity) this effect can be further exacerbated if also considerable dispersion occurs in undisturbed matrix, because as groundwater flow is slowed locally by effective fracture, it also significantly reduces thermal dispersion in this affected area.

In a matrix with slow groundwater flow (0.005 m/day), the beneficial effect of a fracture (i.e. a reduction in the temperature change at the VBHE wall ΔT_b compared with the homogenous case, TAH) is larger in both relative and absolute terms than for a matrix with faster groundwater flow (0.05 m/day). This is because in case where v_∞ = 0.05 m/day, the groundwater flow in matrix is already significantly reduces ΔT_b, therefore thermal gradient created between VBHE and nearby fracture is not as steep comparing to case when groundwater flow in matrix is slower. The thermal plume of interest can be extended (advected) by nearby fracture in slow matrix, (while ΔT_b is reduced). It happens when the flow in the fracture is insufficient to effectively reduce the plume of interest.

4. CONCLUSIONS

The influence of a vertical flowing fracture on the thermal performance of a VBHE was examined under different hydrogeological settings: for two groundwater flows in the matrix (medium and slow), and for different fracture locations relative to VBHE. The thermal performance of VBHE was examined via the temperature change at VBHE wall and extent of the thermal plumes after 30 years of continuous operation, as well as time needed to stabilise temperature change at VBHE wall.

A fracture can have positive or negative effect on the thermal performance of a VBHE. It depends on the interplay of two fracture effects: 1) the ability of fracture to change nearby groundwater velocities in the aquifer matrix (which means increase or decrease in the local apparent thermal conductivity of the matrix) and 2) the ability of the fracture to increase thermal transport from the VBHE (increasing thermal gradient in matrix from the VBHE to the fracture). Fracture reduces the thermal transport from the VBHE if the first fracture effect is dominant and the VBHE is located in the area of slowed down groundwater velocity. The overall fracture effect on the VBHE depends on which of the two fracture effects is dominant.

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Acknowledgements

The authors acknowledge the use of the IRIDIS High Performance Computing Facility and associated services, and the financial support of the Faculty of Engineering and Physical Sciences, University of Southampton.

Table 1 Fixed model parameters

	Fixed parameter, symbol	**Value and units**
Heat input	Virtual depth of VBHE and domain, d_z	100 m
	Constant heat source, Q	J / Ξ [W / m^2 / each m of virtual depth]
	Source heat rate, J	50 [W per each meter of virtual depth]
	Area of heat source, Ξ	1.26×10^{-3} m^2
Geometry	Model domain radius	400 m
	VBHE radius, r	0.05 m
	Heat source radius	0.02m
Material properties	Effective volumetric heat capacity of aquifer, c_{em}	2.8×10^6 J /m^3 /K
	Volumetric heat capacity of water, c_w	4.2×10^6 J /m^3 /K
	Volumetric heat capacity of solid in matrix, c_m	2.2×10^6 J /m^3 /K
	Specific heat capacity of solid in matrix c_m	$c_m = \frac{C_{em}-\epsilon_m C_w}{(1-\epsilon_m)\rho_m} = 814.8$ J /kg /K
	Thermal conductivity of water, λ_w	0.56 W /m /K
	Effective thermal conductivity of aquifer, λ_{em}	2.5 W /m /K
	Thermal conductivity of solid in matrix, λ_m	$\lambda_m = \frac{\lambda_e-\epsilon_m\lambda_w}{(1-\epsilon_m)} = 3.33$ W/m/K
	Porosity, ϵ_m (matrix) ϵ_f (fracture)	30% in matrix, 60% in fracture
	Density of solid material in matrix ρ_m and in fracture ρ_f	2700 kg/m^3
	Density of water, ρ_w	999.9 kg/m^3
	Constant hydraulic gradient in the x direction, valid when the matrix is homogenous (without fracture), M	0.01 (-)
	Hydraulic conductivity of matrix material, K_m based on groundwater flow in homogeneous matrix, v_∞	$K_m = -v_\infty/M$
	Thermal conductivity of solid in the VBHE grout, silica-sand based material (Erol and François 2014)	2.3 W/ m /K
	Density of solid material in grout (Erol and François 2014)	1800 kg /m^3
	Specific heat capacity of solid in grout (Erol and François 2016)	1500 J /kg /K
	Porosity of silica-sand based grout (Erol and François 2016)	0.12
	Hydraulic conductivity of silica-sand based grout (Erol and François 2014)	6×10^{-10} m/s (5.2×10^{-5} m/day)
Time	Reporting time for thermal performance, t	30 years
	Maximum time for simulations, t_{max}	300 years
	Time stepping method	Backward Difference Formula

Table 2 Fracture parameters used in single-parameter analysis

Parameter	**Range (if applicable)**	**Number of steps within parameter range (if applicable)**	**Base value**
Fracture rotation angle relative to x axis direction, around VBHE			Parallel to x axis (parallel to groundwater flow direction in undisturbed matrix)
Fracture thickness (aperture)			0.005 m
Fracture distance from the borehole wall, D_f	0.5 m to 40 m	29	1 m and 5 m
Fracture length			50 m
Hydraulic conductivity ratio of fracture to aquifer material			10000
Shift of fracture mid-length point along its length (parallel to its direction), S_f	-160 m to 160 m	29	0 m (fracture mid-length point is centred with VBHE)