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Inclusion of advection in fractures in the line source equation for analysis of thermal response tests

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ABSTRACT

Proper design of larger ground source heat pump installations, and borehole thermal energy storages (BTES) requires determination of on-site thermal properties of the ground by performing a thermal response test (TRT). The effective thermal conductivity is an important design parameter from TRT that is determined from the line source equation. The line source equation does not include advection and may give incorrect results when groundwater flow is present. This study describes the development and application of a new analytical equation where advective heat in fractured, nonporous rock is accounted for. Including advective heat improves the fit to the measurement data (1.2–77 % better) when applying reasonable values for the thermal conductivity of the ground. The new analytical equation is applicable to all TRTs. Previous studies recommend comprehensive numerical modelling of boreholes affected by groundwater flow. The equation proposed here is an analytical alternative which does not require modelling and is a recommended and cost-effective alternative when groundwater flow affects the thermal properties measured in a borehole heat exchanger in fractured rock.

1. Introduction

Seasonal thermal energy storage has a large potential to reduce the need for fossil fuels (Energiforsk, 2019; Mesquita et al., 2017). Borehole thermal energy storages (BTES) is one technology for seasonal thermal storage. Whether a BTES is profitable or not, depends on its design, operation, availability of waste or inexpensive heat, and its integration into the larger system (Energiforsk, 2019). Important factors for correct dimensioning of a BTES are properties of the ground, such as the undisturbed ground temperature, the effective (in-situ/apparent) thermal conductivity of the ground and the effective thermal resistance of the borehole(s) (Aranzabal et al., 2020; Li et al., 2020; Gehlin and Nordell, 1997). The effective thermal conductivity accounts for both conduction and convection within the ground and may differ from the Fourier's stated thermal conductivity (Liebel et al., 2011). The borehole thermal resistance represents the thermal resistance between the average heat transfer fluid temperature and the borehole wall temperature. Estimations of the effective thermal conductivity of the rock and the effective borehole thermal resistance can be achieved by performing a thermal response test.

The thermal response test (TRT) was proposed by Mogensen (1983) and developed by Gehlin (1998) and Austin (1998). It is an established method for site investigation of the thermal properties of the ground for ground source heat pump installations for both heating and cooling purposes. The test consists in injecting a constant heat rate into a borehole while measuring the up- and down-going fluid flow temperatures. Assuming that end effects and axial variation are small, the setup is conventionally modelled by an infinite line with constant heat rate per length in an infinite homogenous medium of initial uniform temperature. Conduction is assumed to be the only heat transfer mechanism. By using the average temperature for the fluid, borehole wall and the initial state of the ground, an analytical solution is obtained. After sufficiently long time (>10–20 h), the temperature response is well approximated by a simple, linear expression called the infinite line source model (Gehlin and Nordell, 1997; Gehlin, 1998),

$$T_f(t) - T_g = \frac{q^{'}}{4\pi\lambda_{eff}}\left[\ln\left(\frac{4at}{r_b^2}\right) - \gamma\right] + q^{'}R_b \tag{1}$$

where λ_{eff} and R_b are the effective thermal conductivity and borehole thermal resistance, respectively, found from the slope and offset of the measured temperature during a TRT. Injected heat is q' and t is time.

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Nomenclature

Greek letters

α	thermal diffusivity [m^2/s]
η	integration variable [-]
γ	Euler's constant: 0.5772 [-]
λ	thermal conductivity [W/(mK)]

Latin letters

h	advection coefficient [W/(m^2K)]
q'	heat per length borehole [W/m]
R_b	equivalent thermal borehole resistance [mK/W]
r	radius [m]
t	time [s]
T	temperature [°C]
U	modified Darcy velocity [m/s]
u	Darcy velocity [m/s]
x	coordinate [m]

Subscripts

b	borehole wall
eff	effective
f	collector fluid
g	(undisturbed) ground
rock	mineralogic property of rock
w	water

Other values are known parameters explained in the nomenclature. Several alternative analytical models exist, such as the finite line source (Zeng et al., 2002) and the cylindrical line source (Carslaw and Jaeger, 1959, p. 345–6), but the infinite line source is the simplest and most commonly used.

The properties determined by TRTs vary with temperature level in the boreholes and temperature difference between the heat extracting fluid and the borehole due to induced convection (Gustafsson and Gehlin, 2006; Gustafsson et al., 2010; Liebel et al., 2012a, 2012b). This thermally driven groundwater flow is sometimes referred to as the thermosiphon effect and has been observed in several TRTs (Gehlin et al., 2003). This effect reduces the thermal resistance of a borehole (Gehlin et al., 2003; Gustafsson and Gehlin, 2006). More than 40 % reduction in equivalent borehole resistance from a temperature level of about 9 °C to about 23 °C was observed in (Gustafsson and Gehlin, 2006). Gustafsson et al. (2010) recommended to include convection in design tools. Liebel et al. (2012b) enhanced heat extraction/injection per metre borehole by inducing forced convection in the borehole and thereby demonstrated a potential to reduce borehole length (and investment) by 9–25 %. When not accounting for factors like convection, advection, anisotropy and water saturation, the thermal conductivity derived from a TRT will be an apparent, overall, or effective, thermal conductivity which incorporates all these effects and differs from the mineralogic thermal conductivity. Mineralogic thermal conductivities are determined from unsaturated rock core samples in laboratories under pure conduction conditions. Thus, effects of saturation and groundwater movement are not included in the lab measurements. A study comparing the effective and mineralogic thermal conductivity concluded that: "Rock core samples cannot replace thermal response tests", because the laboratory measurements exhibit high variation and deviate too much from the in-situ values obtained in TRTs to establish a formula for their relationship (Liebel et al., 2010).

In Finland, Sweden and Norway, the bedrock is typically impermeable crystalline rock. There are no requirements of grouting, and most boreholes are naturally filled with groundwater. Fractures form pathways for the groundwater. If thermal energy is artificially stored in the ground where groundwater flows, the groundwater will remove parts of the stored energy (Hellström and Gehlin, 1997). The phenomenon is called advection and its effect depends on the quantity, distribution, and temperature of the groundwater flow (Gehlin and Hellström, 2003; Signorelli et al., 2007). Even a minor groundwater flow from a fracture ($\geq 10^{-7} m^3/(sm^2)$) has shown a significant impact on the heat transfer in a model study (Gehlin and Hellström, 2003). The same conclusion was drawn by Signorelli et al. (2007). Groundwater flow can enhance the effective thermal conductivity of the ground and values as high as 64 W/(mK) are reported (Holmberg et al., 2018), about 20 times the expected value based on the mineralogic composition of the rock.

In- and outflowing groundwater in the borehole (advection – transport of heat through fluid motion) has appeared to increase the effective thermal conductivity with TRT measurement time (Witte, 2007; Holmberg et al., 2018; Magraner et al., 2021). This result also occurs in model studies (Signorelli et al., 2007). One explanation is that regional groundwater flow has a higher impact at higher temperature differences between the borehole and the ground (Liebel et al., 2012a). The resulting values for thermal conductivity may thus become much higher than the mineralogic values (Tiwari and Basu 2021; Pastore et al., 2021).

Lumping convective and advective effects (and all other effects, like saturation and anisotropy) into the effective thermal conductivity has the drawback that heat transfer by conduction and groundwater flow are proportional to different phenomena (Ghiaasiaan, 2011). Hence, the effective thermal conductivity cannot fully account for the convective and advective effects. Results from the line source equation (Eq. (1)) when affected by advection may therefore depend on the chosen test conditions such as heat injection rate and test duration. This makes value of the effective thermal conductivity ambiguous.

As an alternative to using an overall effective thermal conductivity, Hakala et al. (2022) used depth specific values of the effective thermal conductivity, so that fractures with groundwater flow obtained own values. Magraner et al. (2021) parameterized the effective thermal conductivity into one static part and one transient, groundwater affected part, thereby reducing the variation in effective thermal conductivity from 27 % to 1.4 %. Signorelli et al. (2007) proposed to use the Peclet number to determine whether the effects of groundwater flow are significant. The Peclet number reveals whether conduction or convection is negligible compared to the other (Signorelli et al., 2007; Ghiaasiaan, 2011). For Peclet numbers of 1, the effects of conduction and convection/advection are of similar magnitude, while convection/advection dominates for high values of the Peclet number. Signorelli et al. (2007) recommended to apply a full numerical simulation if advection is significant. Note that this approach requires the groundwater flow velocity to be known. The velocity of the groundwater is generally unknown and difficult to determine correctly (des Tombe et al., 2019). Tiwari and Basu (2021) modelled porous flow numerically and concluded that advection enhanced the effective thermal conductivity up to about 260 % compared to the mineralogic value. Pastore et al. (2021) modelled natural convection and fracture-based advection in karst limestone numerically and reported that the two phenomena enhanced the BHE efficiency by, respectively ≥20 % and 140–300 %.

An analytical version of the line source model which accounts for advective effects in porous, permeable media is the moving line source model, originally presented by Carslaw and Jaeger (1959). Carslaw and Jaeger (1959) considered the steady-state solution to the case of groundwater flow through the porous ground surrounding the borehole. A transient solution was found numerically by Chiasson et al. (2000) and analytically by Zubair and Chaudry (1996) and Zeng et al. (1997) for finite line sources. Sutton et al. (2003) considered how the borehole thermal resistance changed with time in these cases, and Diao et al. (2004) presented the transient solution for an infinite line with constant heat injection. Jiao et al. (2021) improved the moving finite line source solution to apply for deeper boreholes where depth changes (geological layers, thermal gradient, surface effect), groundwater flow and fluid-solid coupled heat transfer were included.

An alternative to analytical models and direct modelling is the use of g-functions, originally invented by Eskilson (1987). g-functions are defined as the temperature response to a given heat input. The values of g-functions for various conditions are found from numerical modelling and stored for later use (Van de Ven et al., 2021). Claesson and Hellström (2000) found the g-functions, and a simple analytical approximation to the results, for cases of uniform groundwater flow across a finite and infinite borehole.

The moving line source model considers homogenous flow and properties in the ground. The effect of heterogeneity in the ground, i.e., some flow paths are more favourable than others, leading to thermal dispersion, was studied by Metzger et al. (2004); Molina-Giraldo et al. (2011) and Chiasson and O'Connell (2011). Thermal dispersion effects were found to be important for cases where volumetric average groundwater flow is high (Molina-Giraldo et al., 2011; Chiasson and O'Connell, 2011). Comparing model results to real TRT data, a mass-heat transfer analogy model where thermal dispersion was accounted for gave best results compared to g-functions and the moving line source model which do not account for thermal dispersion (Chiasson and O'Connell, 2011). Metzger et al. (2004) implemented the effect of thermal dispersion into the expression for thermal conductivity, so that the moving line source model could account for the effect too.

For fractured but otherwise impermeable rock, the moving line source model does not apply. Fracture flow affects the borehole differently from homogeneous flow in porous media (Signorelli et al., 2007; Gehlin and Hellström, 2003). A borehole may open a new path for vertical flow between fractures so that a large part of the borehole is affected (Gehlin et al., 2003; Liebel et al., 2011; Holmberg et al., 2018). Groundwater may enter the borehole at one or more depths, in different amounts, and leave at one or more other depths. This makes the number of possible configurations infinite, which makes the application of g-functions to these cases impractical.

This study aims to (1) provide an explanation for the apparently increasing effective thermal conductivity with time when advection affects the TRT, and (2) propose how to handle cases where time-dependent effective thermal conductivity occurs in fractured, otherwise impermeable rock, without performing comprehensive numerical modelling.

2. TRT data

Data from three TRTs in Norway (Vensmoen, Lillås and Bjørnegård) and one in Germany (Herford) that are affected by groundwater flow were available to this study. The TRTs are from Vensmoen Eiendom AS in Saltdal municipality; Lillås in Horten municipality; Bjørnegård in Bærum municipality and Herford in Nordrhein-Westfalen, Germany (Fig. 1). Data for the places and the TRTs are given in Table 1. The Norwegian tests are performed in water-filled boreholes equipped with a single U-collector. The bedrock is typical old Norwegian rocks, where the original pores were eliminated during metamorphism and have a crystalline, nonporous structure. The rock types are given in Table 1.

Norwegian drillers commonly provide an estimate of the short-time production yield of groundwater in boreholes in crystalline rock. The method is based on measuring the recovery rate of the groundwater level after draining the borehole with compressed air directly after drilling. For Bjørnegård, the drillers' estimate of the short-time production yield was 15 000 l/h. There is no drillers' estimate at Vensmoen, but several fractures yielding >1000 l/h were reported between 8 and 200 m in the drillers' log. This is also the case for Lillås, having several fractures yielding 50–500 l/h between 17 and 300 m, and an estimated yield of 4 000 l/h in fractures between 6 and 17 m.

Pumping tests for determination of the hydraulic conductivity were not performed in the Norwegian test boreholes. However, the temperature profiles of the test boreholes were measured before and after the TRTs, indicating several fractures with groundwater flow. The interpretation of groundwater flow in the boreholes is based a holistic approach where distinct changes in the temperature profiles, information in the drillers' log, the measured effective thermal conductivity compared to the expected thermal conductivity based on the mineralogical composition of the bedrock at the site are the most important parameters. The interpreted flow pattern in the Vensmoen borehole is illustrated in Fig. 2b, with a high-pressure groundwater flow in the bottom of the well (180–190 m), flowing inside the borehole along the collector, and leaving the borehole via a fracture in the upper part (10–20 m) (Ramstad et al., 2013). Bjørnegård has the same pattern in the upper part of the borehole: inflow at 70–80 m and outflow at 20–30 m (Ramstad and Snilsberg, 2010). At Lillås, the upper part (60–10 m) of the borehole cools down significantly faster than the remaining part of the borehole, indicating groundwater movement. Several fractures are present in the same interval (Eggebø and Ramstad, 2020).

Fig. 1. Location of the sites where the TRT data are retrieved from, marked by red dots and labelled by their names. The map is based on Google maps.

At Herford, the borehole was filled with fine gravel/sand up to 14 m depth, and sealed with clay above this level (Sanner, 2000). A fracture zone was found at about 80 m, yielding about 50 000 l/h (Sanner, 2000). Like at Vensmoen and Bjørnegård, the flow was a high-pressure, upwards flow, presumably exiting through a new fracture zone at 20–28 m depth (Sanner, 2000).

Plotting the average fluid temperature from Vensmoen as a function of time, the temperature quickly approaches a constant value of about 8 °C (see Fig. 5), indicating high groundwater flow. Constant temperature response was also observed at Herford in Germany, even when the heat injection was raised (see Fig. 6). This made the normal method for estimating the thermal conductivity (Eq. (1)) unapplicable (Sanner, 2000). Theoretical estimation of borehole thermal resistance gave R_b = 0.085 K/(Wm), and the mineralogic thermal conductivity of the site is expected to be in the range 1.5–2.5 W/(mK) (Sanner, 2000).

Bjørnegård and Lillås both have shown effects of groundwater flow by achieving effective thermal conductivities about twice as high as the expected thermal conductivity based on the mineralogical composition. The temperature responses at these sites do not become flat like the ones from Herford and Vensmoen (see Figs. 3 and 4). Hence, the groundwater impact is expected to be lower at these sites.

Table 1
TRT-data for the four sites and the rock thermal conductivity (based on the mineralogic composition of the rock).

Place	Rock type	Mineralogic rock thermal conductivity [W/(mK)]	Thermal diffusiv-ity [m^2/s]	q' [W/m]	T_g [°C]	Diame-ter [mm]	Data sources (rock thermal conductivity/TRT data)
Vensmoen	Fauske marble	3.3	1.26e-6	32.05	5.8	165	Jensen (2010)/Ramstad et al. (2013)
Lillås	Basalt, B1	2.4	7.80e-7	39.7	11.2	115	Ramstad et al. (2014)/ Eggebø and Ramstad (2020)
Bjørnegård	Ordovician limestones and shales	2.7	1.26e-6	68.09	8.45	115	Slagstad (2007)/ Ramstad and Snilsberg (2010)
Herford	Mesozoic marls, limestones and shales	2.0 (1.5–2.5)	1e-6 (guessed value)	44.53 70.93	12.2	175	Sanner (2000)/ Sanner (2000)

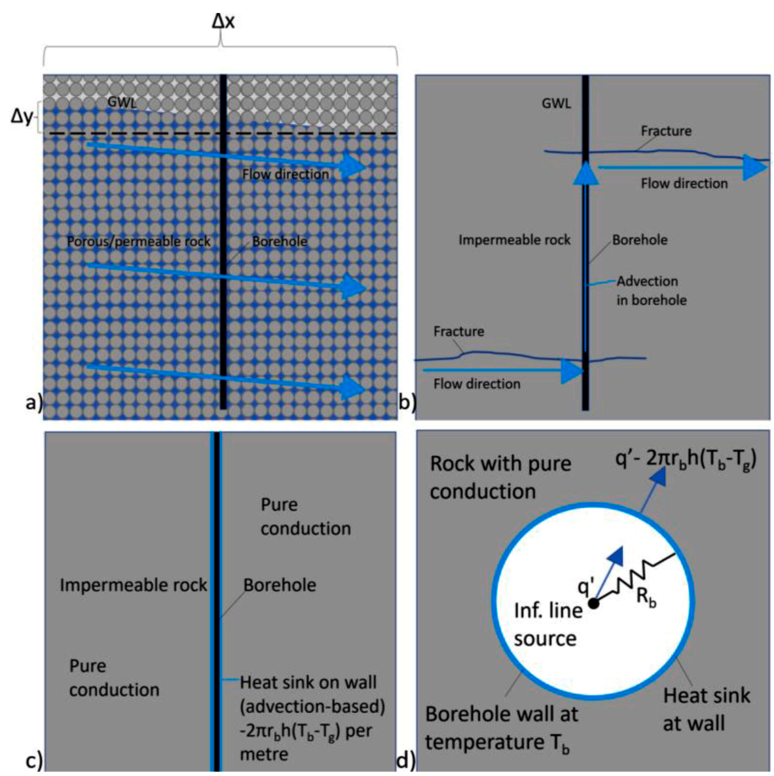

Fig. 2. (a) a borehole in a porous/permeable rock with homogeneous flow, indicated groundwater level (GWL) and hydraulic gradient equal to Δy/Δx, which should be modelled by the moving line source model; (b) a borehole in rock which is impermeable apart from the fractures, with the deeper fracture having higher water pressure than the other fracture causing an upward flow along the borehole (not unusual in Norway/Scandinavia); (c) the simplified situation modelled in Eq. (4): impermeable rock with pure conduction and no fractures, which are replaced by heat sinks on the borehole walls, removing heat by the same mathematical function as advective flow would do; (d) the simplified situation modelled in Eq. (4) seen from above with the line source as a point in the centre, the heat injected per length q' flowing outwards, the thermal resistance R_b between centre and borehole wall, the borehole wall is a heat sink where advection occurs and heat is removed from the model, and the rock has pure conduction of the remaining heat.

3. Method

An expression for the temperature response when groundwater flow affects the result is developed and compared to the standard solution (Eq. (1)). The parameters of both equations were found from parameter fitting in Excel, minimizing the sum of squared deviation between measurements. The first 20 h of data were discarded, as recommended by Signorelli et al. (2007).

3.1. Explaining the apparently increasing effective thermal conductivities

Constantly injecting heat into the ground should cause an ever-increasing ground temperature, but if the TRT is affected by groundwater flow, the measured fluid temperature during the TRT approaches a constant value (see the results for Vensmoen in Fig. 5 and Herford in Fig. 6). This is because advection removes more heat for higher borehole temperatures. An equilibrium between heat injection and heat removal is approached where $T_f(t) - T_g$ is constant. This is in line with simulation results in previous work (Gehlin and Hellström, 2003). Solving Eq. (1) for λ_{eff} and considering the effect of $T_f(t) - T_g$ becoming constant, one obtains

$$\lambda_{eff} = \frac{q^{'}\left[\ln\left(\frac{4at}{r_b^2}\right) - \gamma\right]}{4\pi\left(\left(T_f(t) - T_g\right) - q^{'}R_b\right)} \rightarrow constant \cdot \left[\ln(t) + \ln\left(\frac{4a}{r_b^2 e^{\gamma}}\right)\right] \quad (2)$$

resulting in an apparently ever-increasing effective thermal conductivity instead of temperature. Note that this is only an *apparent* change in thermal conductivity caused by the neglection of a nonnegligible advection. If the line source equation was solved for another parameter, an apparent time-dependency would occur for this parameter too. Equivalently, the estimation of the thermal borehole resistance from Eq.

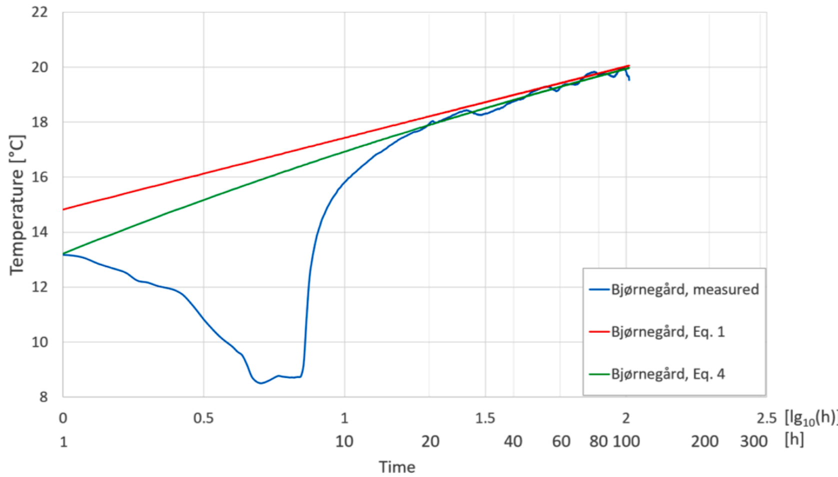

Fig. 3. Measured and modelled temperatures for the TRT results at Bjørnegård: Time is given on a logarithmic scale with base number 10 and corresponding values in hours below.

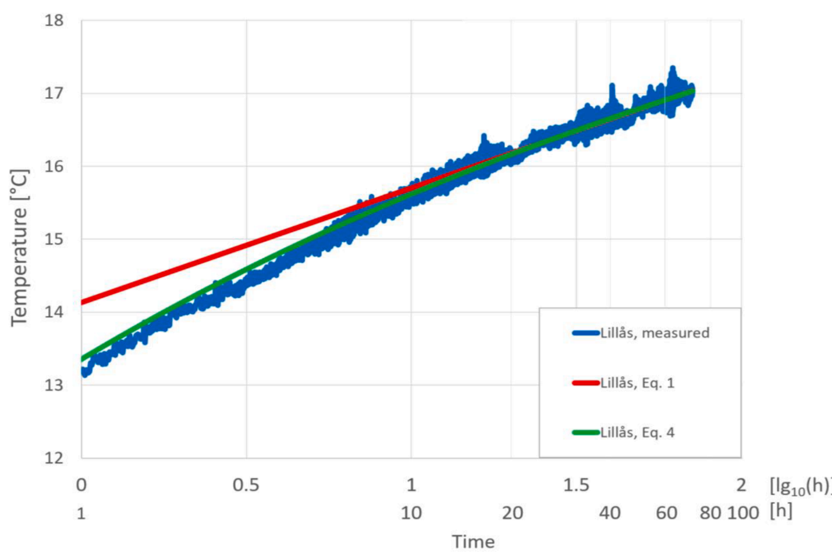

Fig. 4. Measured and modelled temperatures for the TRT results at Lillås: Time is given on a logarithmic scale with base number 10 and corresponding values in hours below.

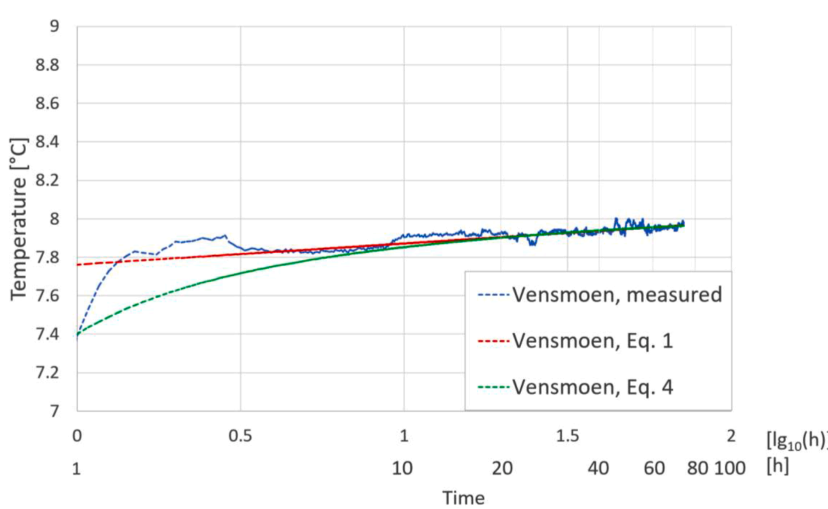

Fig. 5. Measured and modelled temperatures for the TRT results at Vensmoen: Time is given on a logarithmic scale with base number 10 and corresponding values in hours below.

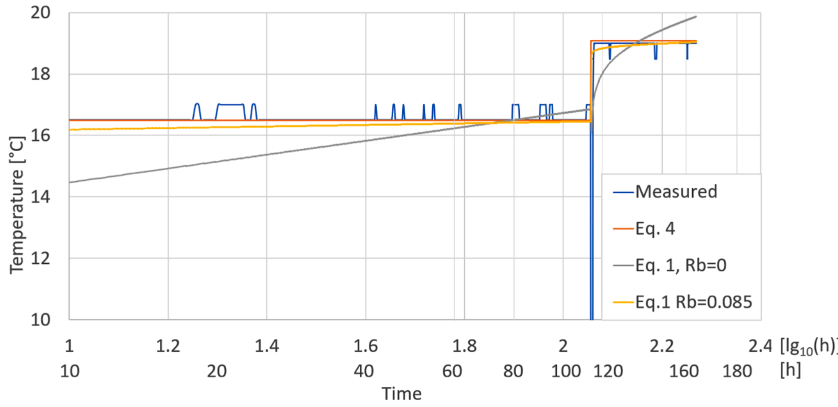

Fig. 6. Using Eq. (1) and (4) to fit the temperature data from Herford, Germany with R_b set to 0 or 0.085 W/(mK): Time is given on a logarithmic scale with base number 10 and corresponding values in hours below.

(1) depends on the result of the effective thermal conductivity. Even though these two parameters are in theory independent of each other, the determination of both using Eq. (1) makes their estimation mathematically dependent on each other: the choice of data to use in optimization and the choice of an optimal value for one parameter, determines the value of the other parameter. Hence, with an apparently increasing effective thermal conductivity, the thermal borehole resistance would appear to decrease with time. I.e., optimizing parameters for Eq. (1), results in a unique pair of effective thermal conductivity and borehole thermal resistance for each time step.

Solving Eq. (1) for the effective thermal conductivity, the value should increase less as the test duration increases. This is because the increase of the logarithm of time decreases with time (the derivative of ln(t) is 1/t). Hence, the increase will diminish with time and the effective thermal conductivity will appear to stabilize with time, but at a higher level than the mineralogic thermal conductivity.

3.2. Including the advection coefficient

Introduction of fractures prevents axisymmetric modelling of the TRT. However, if the fractures appear only in parts of the ground, their presence can be neglected, and the advection effect modelled alone as a heat sink, where heat is lost to the advective flow, see Fig. 2c and d. In this way one obtains an axisymmetric equation. Assuming as before that the depth-averaged temperatures can be used; the equation can still be one-dimensional. To include the advection effects, we apply a new boundary condition at the borehole wall, i.e., at $r=r_b$. It is here assumed that the groundwater removes a heat per length given by the expression for heat removal by convection $2\pi r_b h(T_b - T_g)$ (Incropera et al., 2012). Further, we require that the heat per metre depth conducted into the borehole wall, consisting of bedrock, must equal the injected heat per depth, minus the heat removed by the advective heat sink. Heat conduction into the wall per depth is from Fourier's law of conduction equal to $-2\pi r_b \lambda_{rock} \frac{\partial T}{\partial r}(r_b)$, and injected heat per metre is q'. Combining these terms with the advective term $2\pi r_b h(T_b - T_g)$ gives:

$$-2\pi r_b \lambda_{rock} \frac{\partial T}{\partial r}(r_b) = q' - 2\pi r_b h\left(T_b - T_g\right) \tag{3}$$

where $2\pi r_b$ is the heat transfer area per borehole length, λ_{rock} is the mineralogic thermal conductivity of the ground and h is the advection coefficient, named so in line with textbooks (Incropera et al., 2012) applying the name "convection coefficient" for the convection phenomenon. Applying this boundary condition at $r=r_b$ to the general solution to the infinite line source equation (Ingersoll and Plass, 1948), solving it by Taylor series and truncating the solution after one term one obtains:

$$T_f \approx T_g + q' R_b + \frac{q'}{4\pi r_b} \frac{ln\left[\frac{4\alpha t}{r_b^2 e^{\gamma}}\right]}{\frac{\lambda_{rock}}{r_b} + \frac{h}{2} ln\left[\frac{4\alpha t}{r_b^2 e^{\gamma}}\right]} \tag{4}$$

As for Eq. (1), it has been assumed that some variables can be treated as constants, provided that the variation is small within the range of application, i.e., generally in the interval from 20 to 72 h. These variables include all material properties, q' and the inverse of the denominator. This assumption is not strictly accurate, but the deviation of the denominator's inverse from its average value for 20–72 h was found to be <5 % for Lillås and Bjørnegård. For Vensmoen, the error was 15 % at 20 h, but as the error decreases with time, this is the peak error. After 30 h, the deviation was only 6 %. For Herford, the error could not be estimated because h could not be uniquely defined for this site.

As time approaches infinity (or for very high values of h), Eq. (4) approaches:

$$T_f(t) = T_g + q' R_b + \frac{q'}{2\pi r_b h} \tag{5}$$

which is constant. This is in line with field observations at Vensmoen and Herford, and the theoretical limit for infinitely long time/negligible thermal conductivity (that is: heat in equals advective heat out). This means that the error in the assumption mentioned above should diminish when advection becomes entirely dominant, meaning that the error at Herford is likely to be low. Setting $h = 0$ W/(m^{2}K) in Eq. (4), one obtains Eq. (1). Hence, Eq. (4) is consistent with Eq. (1).

Both versions of the line source equation, with and without the advection coefficient, are applied to data from TRTs affected by groundwater flow to compare them. At Herford, the method was applied with (a) mineralogic thermal conductivity =2.0 W/(mK) and (b) optimizing all three heat transfer parameters (h and R_b and λ_{rock}) requiring that thermal conductivity is within the given interval of 1.5–2.5 W/(mK). The first 20 h of data are discarded as recommended by Signorelli et al. (2007). The model errors are highest for both models during these first hours.

Parameter fitting is used to find two parameters for each equation: The effective thermal conductivity and the thermal borehole resistance is found for Eq. (1) and the advection coefficient and the thermal borehole resistance is found for Eq. (4). The thermal conductivity in Eq. (4) is set equal to the mineralogic value. This ensures that Eq. (4) has the same degree of freedom, i.e., the same prerequisite to achieve good curve fits, as Eq. (1). In other words, comparing two equations with different number of parameters, one would expect the equation with most parameters to give best fit, because this equation has more parameters that can be adjusted to give good fit than the other. One could determine the thermal conductivity in Eq. (4) from parameter fitting too, but then a better fit to the data can be due to the higher degree of freedom.

3.3. Evaluating the significance of the advection coefficient

To demonstrate the impact of the advection coefficient, some examples of expected heat losses are estimated for various values of the advection coefficient. The loss per metre length due to the groundwater flow during a TRT is:

$$2\pi r_b h\left(T_b - T_g\right) \approx \frac{q^{'}h}{2}\frac{ln\left[\frac{4\alpha t}{r_b^2 e^{\gamma}}\right]}{\frac{\lambda_{rock}}{r_b} + \frac{h}{2}ln\left[\frac{4\alpha t}{r_b^2 e^{\gamma}}\right]} \tag{6}$$

and the groundwater flow that creates the energy loss can be estimated by

$$\dot{m_w} = \frac{2\pi r_b L h\left(T_b - T_g\right)}{c_{p,w}\left(0.5\left(T_f + T_b\right) - T_g\right)} \tag{7}$$

The presented examples have typical values for heat injection rate and borehole dimensions. The impact of the advection coefficient on the effective thermal conductivity is found by constructing temperature responses with Eq. (4) and analysing them by Eq. (1). Based on the results, guidelines for when to use Eq. (1) and when to use Eq. (4) are provided. Eq. (4) is also compared to the moving line source as presented by Diao et al. (2004), with the additional term $q^{'}R_b$ to achieve average collector fluid temperature T_f rather than modelled ground temperature:

$$T_f - T_g = R_b q^{'} + \frac{q^{'}}{4\pi\lambda_{rock}}e^{\frac{Ux}{2\alpha}}\int_0^{r^2/4\alpha t}\frac{1}{\eta}e^{-\frac{1}{\eta}-\frac{U^2 r^2 \eta}{16\alpha^2}}d\eta \tag{8}$$

where $U = \frac{u\rho_w c_{p,w}}{\rho_{rock}c_{p,rock}}$, u is the Darcy velocity and x is the distance from the borehole centre in flow direction. Diao et al. (2004) version of the moving line source equation was used in the comparison because it applies an infinite line source just like Eqs. (1) and (4). Comparing Eq. (4) to a finite moving line source would involve comparison of two different factors at the same time (finite line and porous media), making it unclear which of the factors that caused the differences in the results. As for Eqs. (1) and (4), two parameters of the moving line source equation were optimized to minimize the deviation from the measurements. These parameters were R_b and the Darcy velocity.

4. Results

4.1. Applying Eqs. (1) and (4) to TRT results

The modelled and measured temperature responses are shown in Fig. 3 through Fig. 6. Eq. (1) and Eq. (4) are fitted to data after 20 h and give similar lines during the rest of the TRTs. Both equations show the temperature jump after changed heat injection at Herford. Eq. (4) is consistently better than Eq. (1) and reduces the model error by 1.2, 35, 66 and 77 % compared to Eq. (1). The numerical results are shown in Table 2. For Lillås and Bjørnegård, Eq. (4) gives coefficients of determination>0.90, whereas Eq. (1) gives 0.60 and 0.88. For Vensmoen, the coefficients of determination are nearly identical: 0.48 for Eq. (1) and 0.49 for Eq. (4), and significantly lower than for the other sites. A model always predicting the average value of a dataset will achieve a coefficient of exactly zero, and the data at Vensmoen are all close to the average, thus a positive value should be considered good.

The thermal conductivities obtained by Eq. (1) are nearly twice the mineralogic values at Lillås and Bjørnegård, and about 18 and infinitely much higher at Vensmoen and Herford, respectively. The two last mentioned sites are the sites with highest impact of advection in the TRTs.

Results for R_b would change with a time-varying λ_{eff}. However, as the two parameters are found together when optimizing, both are shown here for completeness and transparency of the work. The presented values are not asymptotic values, but values obtained for the period from 20 h till the end of each TRT, which is a standard way of finding these parameters. Eq. (4) gives lower thermal borehole resistances than Eq. (1) for all sites and reasonable convection coefficients (Incropera et al., 2012 chapters 8–9).

For Vensmoen, the temperature slope in Fig. 5 is hardly detectable to the eye, changing only ≈0.02 °C from 20 h to 70 h, making the effective thermal conductivity very high (58.8 W/(mK)). For Herford, no slope could be detected, and several pairs of h and R_b gives similar fit. In Table 3, five different sets of parameters are presented, giving coefficients of determination of 0.91–0.98. This is because the lack of slope makes it impossible to provide two different values for the two parameters – a change in the first is offset by a change in the other. This is seen by using Eq. (5) twice with the two different heat fluxes and resulting temperatures in the TRT:

$$16.5^{\circ}\mathrm{C} = 12.15^{\circ}\mathrm{C} + 44.53\frac{\mathrm{W}}{\mathrm{m}}\cdot\left(R_b + \frac{1}{\pi 0.175h}\right) \tag{9}$$

$$19.0^{\circ}\mathrm{C} = 12.15^{\circ}\mathrm{C} + 70.93\frac{\mathrm{W}}{\mathrm{m}}\cdot\left(R_b + \frac{1}{\pi 0.175h}\right) \tag{10}$$

If Eqs. (4) and (5) are describing the TRT well, the term $\left(R_b + \frac{1}{\pi 0.175h}\right)$ should get the same value from both Eqs. (8) and (9). The temperature measurements were ±0,25 °C, giving overlap for:

$$0.093 \leq R_b + \frac{1}{\pi 0.175h} \leq 0.100 \tag{11}$$

Thus, the equations are consistent, but do not provide separate values of h and R_b.

$$T_f(t) \approx T_g + q^{'}\cdot(0.965 \pm 0.035) \tag{12}$$

for all heat rates up to 71 W/m. 71 W/m was the highest applied heat rate in the TRT and is thus the highest value one can use in Eq. (12) with high confidence. Fig. 6 shows the result of this approach (labelled "Eq. (4)") together with optimized effective thermal conductivity in Eq. (1), using the two different values of R_b from (Sanner, 2000). The modelled temperature response gives a poor fit for Eq. (1) with R_b = 0.00 mK/W,

Table 2
Parameters of the Eqs. (1) and (4): bold values are input data; the other values are results. The error is the sum of squared deviations between model and measurement from 20 h and onwards. The coefficient of determination (R^2) for each case is also reported.

Site	Thermal conductivity [W/(mK)]		Borehole thermal resistance [mK/W]		Advection coefficient [W/(m^{2}K)]	Error reduction [%]	Coefficient of determination [-]	
	λ_{eff} Eq. (1)	λ_{rock} Eq. (4)	R_b Eq. (1)	R_b Eq. (4)	h Eq. (4)		R^2 Eq. (1)	R^2 Eq. (4)
Lillås	4.63	2.4	0.063	0.034	7.53	77	0.60	0.91
Bjørnegård	4.79	2.7	0.075	0.039	4.88	66	0.88	0.96
Vensmoen	53.1	3.3	0.061	0.042	58.8	1.2	0.48	0.49
Herford	Infinite	2.0	0 or 0.85	0.084–0.099	≥186	91 or 35	0.75 or 0.97	0.95–0.98

Table 3
Results for optimizing parameters in Eq. (4) to fit the Herford data with various approaches: for the highest value of h, the used value of mineralogic thermal conductivity is negligible and thus irrelevant. The coefficient of determination (R^2) for each case is also reported.

Parameter/ evaluation of fit	Optimization with respect to data when q'=45 W/m	Optimization with respect to data when q'=71 W/m	Optimization with respect to all data after 20 h	Optimization with respect to all data after 10 h	Optimization with respect to all data after 20 h and λ_{rock} is optimized too
h [W/(m^{2}K)]	139	193	186	194	1.01E+07
R_b [mK/W]	0.087	0.081	0.084	0.099	0.0976
λ_{rock} [W/(mK)]	2.0	2.0	2.0	2.0	irrelevant
R^2	0.91	0.91	0.95	0.98	0.98

Since the lack of temperature slope prevents the determination of h versus R_b, one can merge R_b and h into a single parameter and use Eq. (5) in the new form:.

better for Eq. (1) with $R_b = 0.085$ and clearly best for Eq. (4) with $R_b + \frac{1}{\pi 0.175h} = 0.965$.

4.2. Comparison to the moving line source equation

Comparing Eq. (4) to the moving line source equation (MLS), the coefficients of determination are higher for Eq. (4) than the MLS at all the Norwegian sites (see Table 4). For Bjørnegård, the difference in coefficients of determination is smaller than the roundoff error in Table 4, and not visible. The MLS is better at modelling the data from Herford, but again the difference in coefficients of determination is smaller than the roundoff error. At Bjørnegårs and Herford, the coefficients reach, respectively 0.96 and 0.98, whereas the results at Vensmoen and Lillås differ significantly between the models. The coefficients of determination are 0.69 and 0.91 for Lillås and 0.007 and 0.49 at Vensmoen, where Eq. (4) achieves the better result in both cases.

Estimating the Darcy velocity U for Eq. (4) by means of Eq. (7), water properties and flow area, the Darcy velocities for Eq. (4) and the MLS are not very similar, but within the same order of magnitude. The borehole thermal resistance values are highly different between the models, being 74–100 % lower for the MLS than for Eq. (4), and exactly 0 mK/W for Lillås and Vensmoen.

4.3. Significance of the advection coefficient

An example of heat losses due to advection is shown for various values of h in Fig. 7. The figure shows that the heat removed by advection during the TRTs for h-values ranging between 5 and 50 W/(m^{2}K) is about 0.7–2.7 kW, and that the effect starts from 0 kW and increases with time. This is because the borehole temperature increases with time and the groundwater flow removes more heat from a borehole with a higher temperature. However, the curves all become flatter with time, and should theoretically reach a steady state where the heat injection is in balance with the heat removed by conduction and advection. The curves are made by applying some typical values in Eq. (6): q' is 40 W/m, the borehole depth is 100 m and the applied mineralogic thermal conductivity was set to 2.9 W/(mK).

Eq. (4) was used to construct temperature responses for the same case with various advection coefficients and borehole radii. Analysing these temperature responses by Eq. (1), the resulting effective thermal conductivities are demonstrated in Fig. 8. The effective thermal conductivities estimated in this manner increase rapidly with time during the first hours, and then slowly after about 20 h. For the highest applied advection coefficient, 15 W/(m2K), the increase with time is visible throughout the 72 h of modelled test duration, but for lower values of 5 and 7.5 W/(m2K), the increase of effective thermal conductivity with time is low and may be interpreted as a converged result. The estimated effective thermal conductivities in Fig. 8 increase with borehole radius, which ground properties should not. The results after about 20 h are ≈40–240 % larger than the applied mineralogic thermal conductivity.

4.4. When to apply Eq. (4) instead of Eq. (1)

A procedure for when to apply Eq. (1) or 4 is described in Fig. 9. Eq. (1) is the suggested starting point, whereas for significantly higher effective than mineralogic thermal conductivities, Eq. (4) should be used instead. Challenges related to flat profiles are recommended solved by a simple relationship like the one obtained in Eq. (12).

5. Discussion

The results for time development of the effective thermal conductivity when applying Eq. (1) to sites with advection are the same in this work as in many other works: for low advection effects ($h \leq$ca 7.5 W/(m^{2}K) in Fig. 8), an effective thermal conductivity found by Eq. (1) would not show a clear increase with time, but it would be markedly higher than that of the rock. A reasonable explanation for the increasing thermal conductivity result is found in Eq. (2): When Eq. (1) is applied to a site where a steady state temperature exists within timescales like the duration of a TRT (i.e., a site with advection), the presumed ever-increasing temperature in Eq. (1) will create an apparently time-dependent effective thermal conductivity when the measured temperature raise stagnates. However, the temporal development of the effective thermal conductivity follows the logarithm of time, and therefore may seem to stabilize for low advection effects. The apparent time-dependency of the effective thermal conductivity is easier seen for higher advection effects (f. ex. $h = 15$ W/(m^{2}K) in Fig. 8).

An analytical expression for the temperature development when advection through fractures affects the TRT is developed in Eq. (4). It is similar to Eq. (1) but includes an advection coefficient and stabilizes with time for any positive, nonzero values of advection coefficient and thermal conductivity. All advection affected TRT results would stabilize if they continued for sufficiently long time (Carslaw and Jaeger, 1959; Gehlin and Hellström, 2003) unlike the temperature in Eq. (1), which gives an ever-increasing temperature for all positive, nonzero parameters. Hence, the apparent time dependency of the parameters in Eq. (1) is

Table 4
Comparison of the results of using Eq. (4) and the moving line source (MLS) equation as presented by Diao et al. (2004).

Site	Thermal conductivity [W/(mK)]	Borehole thermal resistance [mK/W]		Darcy velocity [m/s]		Advection coefficient [W/(m^{2}K)]	Coefficient of determination [-]	
	λ_{rock} Both models (input)	R_b MLS	R_b Eq. (4)	u From Eqs. (4) and (7)	u MLS	h Eq. (4)	R^2 MLS	R^2 Eq. (4)
Lillås	2.4	0.00	0.034	4.90E-06	7.62E-06	7.53	0.69	0.91
Bjørne-gård	2.7	0.010	0.039	3.15E-06	1.96E-06	4.88	0.96	0.96
Vens-moen	3.3	0.00	0.042	2.43E-05	1.21E-05	58.8	0.007	0.49
Herford	2.0	0.0070	0.084–0.099	na	1.07E-05	≥186	0.98	0.95–0.98

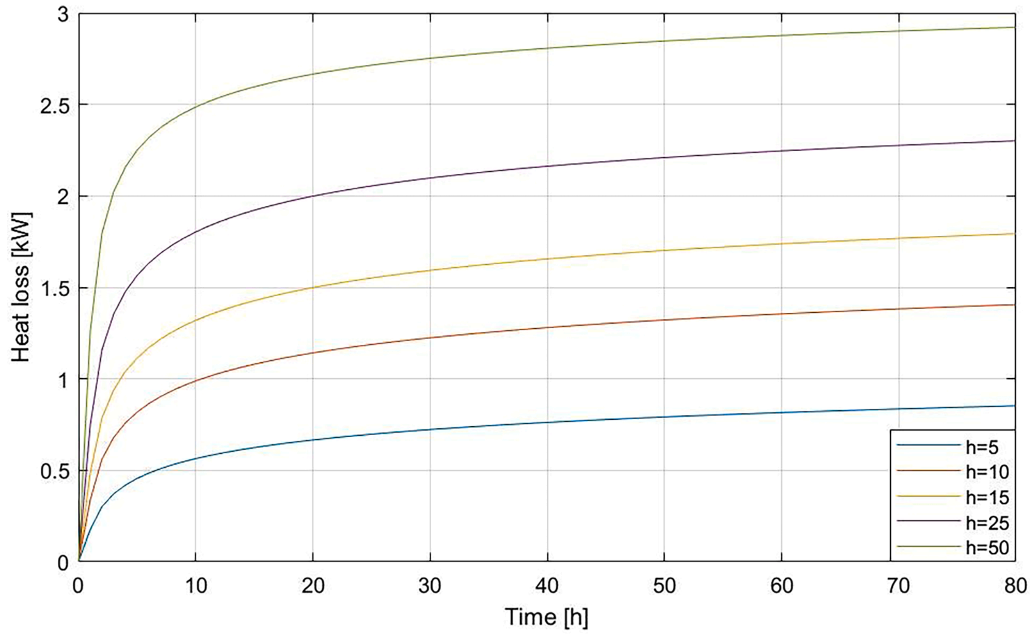

Fig. 7. Theoretical heat losses due to advection during TRTs where 40 W/m is injected, 100 m of the borehole length is affected by convection with a given advection coefficient h [W/(m^{2}K)] and the borehole radius is 5.75 cm. $h = 5$ W/(m^{2}K) is close to the values for Lillås and Bjørnegård and $h = 50$ is a very high value, similar to that at Vensmoen.

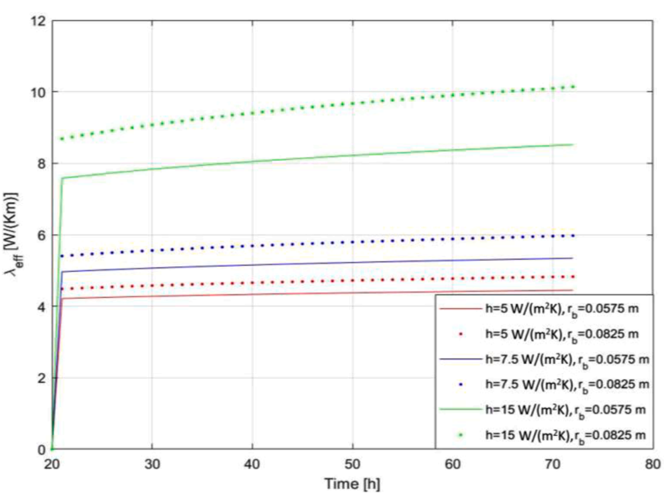

Fig. 8. Result of applying linear regression and Eq. (1) to temperature series developed with Eq. (4) with $\lambda_{rock} = 2.9$ W/(mK).

removed by including the advection coefficient. The advection coefficient is the same as the convection coefficients in standard textbooks on heat transfer (e.g., Incropera et al., 2012), and thus has a physical meaning and is in accordance with existing literature. It should, in theory, depend only on the borehole hydraulic diameter (Incropera et al., 2012, p. 558) and flow. No difference is made in whether the flow is naturally induced (natural convection/thermosiphon effect) or externally driven (forced convection/advection). Like Eq. (1), Eq. (4) is not a complete solution to the transient heat conduction problem, but the error diminishes for higher values of time or groundwater flow. As the model error of Eq. (4) decreases with time, it would be better to perform even longer TRTs, up to f.ex. 100 h, and discard even more initial data than 20 h to get lower model errors.

The advection coefficient is here added as a boundary condition, whereas other works apply the advection term in the heat equation (Carslaw and Jaeger, 1959; Kohl et al., 2002; Diao et al., 2004), or as part of the diffusion parameters in the heat equation (des Tombe et al., 2019). When the advection phenomenon only takes place in the borehole and in a few fractures like the cases studied here, the boundary condition approach is a more physically correct approach than including advection everywhere, as the heat transfer in the rock is pure conduction. For porous media on the other hand, the approach of including the advection term in the heat equation should be the best choice. In a numerical study like those by Kohl et al. (2002) and Simon et al. (2020), it would be possible to include the advection coefficient in the heat equation and then set it to 0 W/(m^{2}K) in the rock and nonzero in the borehole and fractures, but in an analytical approach like here, having one unique, constant value of h at the boundary only is the simplest and a reasonably physically correct approach.

Fig. 3 through Fig. 6 show that both Eqs. (1) and (4) give good curve fits, with coefficients of determination >0.90 for most sites for Eq. (4), and >0.60 for Eq. (1) for the same sites. For Vensmoen, where the data are always close to the average value, and the two models give nearly identical coefficients of 0.48 and 0.49. Eq. (1) gives unrealistically high thermal conductivities (2–18 times higher than the mineralogic values) when groundwater affects the TRT, whereas Eq. (4) applies realistic values and still achieves better fit. Hence, the findings in this study corroborate that Eq. (4) describes the physics well. This is an improvement to the work by Magraner et al. (2021) where parameterization of the effective thermal conductivity had no physical meaning.

Signorelli et al. (2007) recommended that boreholes with groundwater flow should be modelled numerically as the impact of the groundwater flow was significant and the physics complex. Eq. (4) is an easier way to include this impact. It removes the need for expensive, time-consuming modelling which requires modelling skills and trial and error for estimating the effective thermal conductivity and groundwater flow. Eq. (4) can be used in the same way as Eq. (1) and will get estimated groundwater flow as a direct result in addition to R_b and thermal conductivity. For heterogenous ground, one can divide the borehole length into sections and evaluate each section separately (Acuña et al., 2009), using either Eq. (1) or Eq. (4) and depth specific measurements. Measurements of the temperature profile before and after a TRT with a single temperature probe is a cheap and simple way to determine the length of the borehole that is affected by groundwater flow (Holmberg et al., 2018).

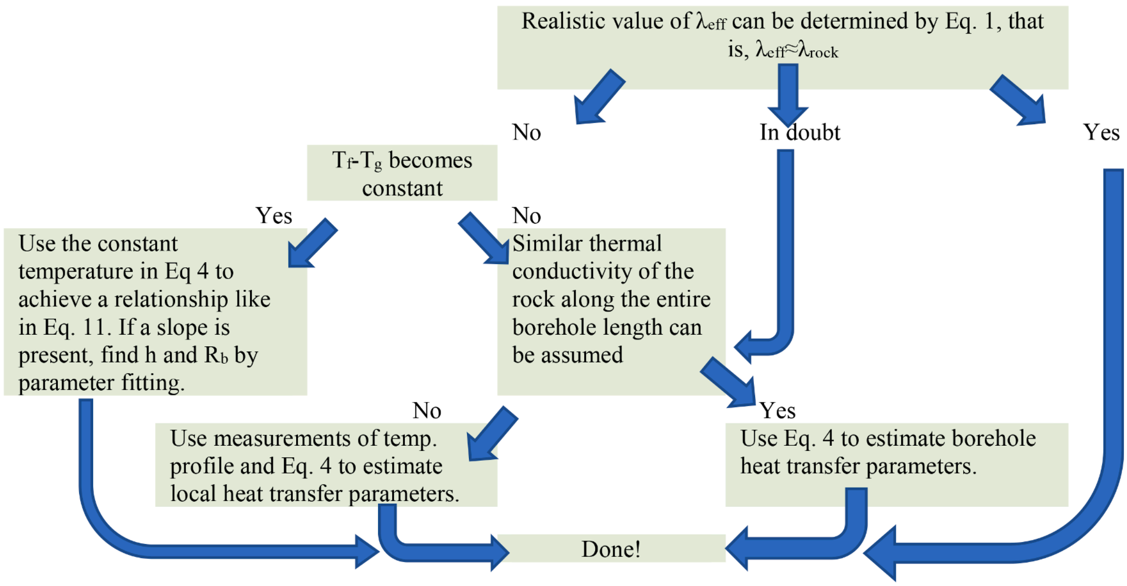

Fig. 9. Suggested procedure for when to use Eq. (1) and when to use Eq. (4).

Natural convection, or the thermosiphon effect, may also occur within the borehole, creating internal circulation, which should affect R_b. The thermosiphon effect may also potentially enhance or reduce the net advective flow (Gehlin et al., 2003), thereby affecting the advection coefficient h. The developed method finds h based on the *net* flow and does not distinguish between different contributions to the flow. Natural convection is reported to be negligible for heat injection rates below 20 W/m (Hakala et al., 2022), but the heat rates in the TRTs reported here were>20 W/m. The importance of advection vs. natural convection for the net flow depends on the magnitudes of the driving forces for the two phenomena, and in theory, either effect could be larger (Ghiaasiaan, 2011). However, in another study of advective effects, advection was reported to be one order of magnitude larger than those of natural convection (Pastore et al., 2021), and natural convection/the thermosiphon effect is thus probably of low importance compared to advection in this work.

Eq. (4) gave low values of R_b for Lillås, Bjørnegård and Vensmoen (≤0.042 mK/W whereas 0.06–0.08 mK/W are typical values for single U-tube collectors Gustafsson and Gehlin, 2006; Spitler et al., 2016). This can be explained by that: (1) the groundwater entering the borehole may vary in temperature (this was observed at Vensmoen), and the measured undisturbed temperature may therefore differ from the true undisturbed temperature, giving an erroneous R_b; (2) enhanced groundwater movement enhances heat transfer and reduces R_b. This result has been found in previous work on convection, where up to 50 % reduction in R_b was found (Liebel et al., 2012b; Gustafsson and Westerlund, 2010). Hence, the value of R_b at Herford is higher than expected for a site with high groundwater movement (>0.08 mK/W).

One possible explanation for the high thermal borehole resistance at Herford is that the flow pattern or affected borehole length differs between the places with high and low R_b-values, as this effects the results (Signorelli et al., 2007). Another factor is the larger borehole diameter at Herford (see Table 1), which enhances R_b. Whether the R_b values found by Eq. (4) also depend on temperature level and heat injection rate was not investigated here.

Some challenges with Eq. (4) and means to solve them are: (1) The thermal conductivity of the rock is unknown and should be a result from the line source equation. Values for thermal conductivity from the literature were used here to make the comparison with the standard line source equation fair. However, the effective thermal conductivity of the ground could be optimized together with h and R_b. (2) When the TRT result shows no temperature slope at all, it is not straight forward to apply Eq. (4). However, the temperature response for heat rates lower than the highest one tested is well described by Eq. (12), where the sum of the term $R_b + \frac{1}{2\pi r_b h}$ can be found from a TRT result. (3) The advection coefficient may change if the groundwater flow changes. Accounting for such changes requires more information than a TRT provides. This is a challenge with both Eqs. (1) and (4). Long-term measurements and quantification of the groundwater flow would be advantageous to determine if and how the advective contribution changes with time. However, Eq. (4) with a constant coefficient is still a good alternative compared to neglecting advection entirely.

It is not investigated here whether Eq. (4) is applicable in porous rock. The modelling of advection effects as a heat sink on the borehole wall should enable Eq. (4) to provide reasonable fits for advection effects in porous rocks, but the temperature field surrounding the borehole would be wrongly modelled as Eq. (4) assumes axis-symmetry. Hence, the physical soundness could be questioned. The MLS and Eq. (4) give similar fits at two of the sites, yet very different borehole thermal resistances in all cases. The calculated thermal resistances are even lower for the MLS model than for Eq. (4), with values as low as 0 mK/W for Lillås and Vensmoen. These low estimates of the thermal resistances indicate potential limitations in the MLS model when applied to nonporous rock.

The low estimates could originate from (1) the flow creating unusually good thermal contact, making R_b virtually 0 mK/W or (2) that the obtained parameters with the MLS model at Lillås and Vensmoen do not represent any physical properties but are results of pure curve fitting. The Norwegian sites are all in fractured crystalline rock where Eq. (4) is expected to be most physically correct and also gives the best fits. The German site, Herford, had so high groundwater yield that the type of advection scheme seems to be irrelevant, which might be why the MLS model and Eq. (4) gave nearly identical fits here, both reaching coefficients of determination of 0.98. Eq. (4) is based on more simplifications than the MLS model, but it is both simpler and easier to use than the MLS and numerical alternatives.

6. Conclusion

Thermal response tests and the line source equation (Eq. (1)) are used for proper dimensioning of ground source heat pump installations and of BTES. When regional groundwater flow affects the test, Eq. (1) predicts an ever-increasing effective thermal conductivity. The reason is that advective heat is not accounted for in the standard solution and advection behaves differently from conduction: Advective heat increases until the heat injection and removal are in balance so that a constant temperature level can occur. A solution where the advective contribution from fractures is accounted for and estimated was found in this work (Eq. (4)) and gave both improved fits to measurement data (1.2–77 %) despite that still only two parameters were adjusted and involved physically reasonable values of the thermal conductivity. The parameters of both equations can only be determined separately if there is a slope in the measured temperature response data. Otherwise, the parameters of Eq. (4) can be merged into a single parameter which can be found (Eq. (12)) to predict the temperature response of a borehole up to a certain limit. The proposed solution is an effective method that accounts for the effect of groundwater flow on TRTs in fractured, nonporous rock, avoiding the need for expensive, advanced, and time-consuming numerical modelling. Its potential for application in porous media is not investigated here, but both Eq. (4) models the data in all Norwegian sites at least as good as the MLS and significantly better at Lillås and Vensmoen. The obtained thermal borehole resistances are 74–100 % smaller for MLS than for Eq. (4), and 0 mK/W in two cases, indicating that Eq. (4) describes the physics better. Eq. (4) has the advantage of being simpler than the MLS in use, but also involves some mathematical simplifications and neglects the non-symmetric conditions created by the flow.

7. Further work

Advection introduces an additional unknown parameter to be determined from the same amount of data as the two established parameters, R_b and λ_{eff}. To enhance confidence in the obtained results for all three parameters, more information would be beneficial. This could be obtained without enhanced costs using either two heat injection rates during the TRT or measurement of the temperature profile before and after the test. The latter method was first recommended by Liebel et al. (2011) and is an established practice. If the exact times for these measurements are provided, an estimation of the groundwater flow could be obtained from these results using the method presented by Kvalsvik et al. (2022), giving an estimate for the advection coefficient h known through Eq. (7). A better, but costlier solution is the use of a distributed TRT, where the temperature profile in the borehole is measured during the TRT (Acuña et al., 2009), to determine h. The latter method requires additional equipment, expertise, and effort during the TRT.

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CRediT authorship contribution statement

K.H. Kvalsvik: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Visualization. **H. Holmberg:** Resources, Investigation, Data curation, Writing – review & editing. **R.K. Ramstad:** Supervision, Writing – review & editing. **K. Midttømme:** Funding acquisition, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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