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# Response Functions and Thermal Influence for Various Multiple Borehole Configurations in Ground Coupled Heat Pump Systems

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*Abstract*: - Ground coupled heat pump (GCHP) utilizes the immense renewable storage capacity of the ground as a heat source or sink to provide space heating, cooling, and domestic hot water. GCHP systems are generally comprised of water source heat pumps and ground heat exchangers (GHEs). Consisting of closed-loop of pipes buried in boreholes, ground heat exchangers (GHEs) are devised for extraction or injection of thermal energy from/into the ground. Despite the low energy and lower maintenance benefits of ground-source heat pump systems, little work has been undertaken in detailed analysis. Many models, either numerical or analytical, have been proposed to analyze the thermal response of vertical heat exchangers that are used in ground coupled heat pump systems (GCHP). In both approaches, most of the models are valid after few hours of operation since they neglect the heat capacity of the borehole. In this paper, we present for three various multiple borehole configurations a comparison between g-functions, which will be calculated after an analytical model of final line source and g-functions, obtain with numerical model derived from the work of Eskilson. A case study is presented to show how the ground temperature changes with time for various multiple borehole configurations.

*Keywords*: - Geothermal Heat Exchanger; Heat Transfer, Heat Conduction, Non-dimensional Temperature Response Factors, Thermal Influence

## 1 Introduction

Underground Thermal Energy Storage (UTES) systems have recently shown an increasing interest. There are a great number of UTES systems available today. When the borehole is used for heating as well as cooling, one may speak of heat storage, i.e. heat is being led through the borehole for cooling and will later be used for heating. There are several different types of UTES storage, but the technique which is said to have the greatest potential for large stores of thermal energy is the so called borehole heat storage. The thermal energy is then stored in the bedrock between the boreholes [1]. Various concepts of these systems are presented and it was concluded that, from the techno-economic standpoint, it is most appropriate to use the BTES (Borehole Thermal Energy Storage). Natural heat systems make it possible to utilize solar energy which is stored passively in air, ground and water. Using a heat pump, this low temperature heat can be extracted/rejected for heating/cooling purpose [2].

Ground coupled heat pump (GCHP) systems exist for many years and the concept is widely accepted as one of the best renewable energy technology. Until recently, the initial cost of these systems hindered their growth, especially for residential purposes. Due to reduced energy consumption and maintenance costs, GCHP systems, which use the ground as a heat source/sink, have been gaining increasing popularity for space conditioning in buildings [3, 4]. The efficiency of the GCHP systems is inherently higher then that of air source heat pumps because the ground maintains a relatively stable temperature throughout the year. The system is environment-friendly, producing less $CO_2$ emission than the conventional alternatives. The efficiency of such a system depends on how much heat is extracted (in winter) or rejected (in summer) in the ground. The geothermal heat exchanger (GHE) is devised for extraction or injection of heat from/into the ground. These systems consist of a sealed loop of pipes, buried in the ground and connected to a heat pump through which water/antifreeze is circulated. The GCHP systems require a certain plot of ground for installing the GHEs, which often becomes a significant restriction against their applications in densely populated cities and towns. The vertical GHE is the most popular design of GCHP systems currently employed, since it requires less ground area than the horizontal trench systems. These boreholes should be separated by certain distances to ensure long term operation of the system [5, 6]. In the vertical borehole systems the GHE consists of a number of boreholes (of diameter 75-150 mm), each containing single or double U-tube pipes. In the case of vertical heat exchangers, in most configurations, the fluid passes through U-tubes in the form shown in Fig. 1. The borehole annulus should be grouted (usually over its full depth) with backfilling materials that provide thermal contact between the pipe and the soil/rock and to protect groundwater from possible contamination [6]. The depth of the borehole typically varies between 30 m and 120 m.

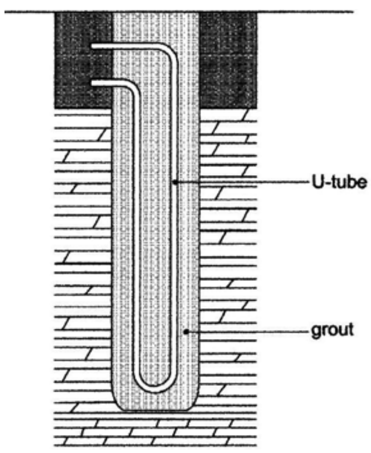


Fig.1: Ground heat exchanger.

For the design of vertical boreholes, we are interested in the heat transfer between the working fluid and the ground. There have been a number of models based on some analytical solutions or numerical solutions that were used for designing vertical boreholes used in GCHP systems. As we will see in the following section, these models often give the same results (numerical solution shares the flexibility associated with analytical solutions). The main objective of this paper is to show how ground temperature rise or fall over a number of years for various multiple borehole configurations.

The thermal influence between several various multiple borehole configurations has long-term character. Because of that, it is reasonable to find non-dimensional response g – functions, which include complete information about thermally influence between individual time periods. For better illustration and for comparison we will compare g-functions for three various multiple borehole configurations. One will be calculated after analytical model of final line source and the other will be obtain with numerical model derived from the work of Eskilson (1987). For all three configurations the changes of the temperature in the neighborhood of boreholes are illustrated.

# 2 Heat conduction around boreholes

## 2.1 Conduction of heat

The diffusivity, *a*, depends entirely on material properties and shows whether a material is a good thermal conductor or not – the better heat conductor the higher the parameter *a*. The diffusivity is expressed: $a = \lambda / C$.

The fundamental equation of heat conduction shows how the temperature depends on *a*:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{a}\frac{\partial T}{\partial t}. \tag{1}$$

The temperature, *T*, in a point with the coordinate (*x*,*y*,*z*) is determined by the time, *t*, and by the diffusivity, *a*.

Transient (time dependent) conditions occur, for example, when there is a sudden change of temperature in a body, a periodically altering temperature or a time dependent supply of heat. During stationary conditions the heat capacity looses importance and so does the time derivative. The equation of heat conduction can then be represented by the Laplace equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0. \tag{2}$$

The two equations above are valid for an infinite, solid material in a Cartesian coordinate system. The material has to be homogenous and isotropic.

## 2.2 Theory of infinite line source

Line source theory is based on simplification of the general 3-D heat conduction equation with a cylindrical heat source as given by equation 3:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2}. \tag{3}$$

This is the transient heat conduction equation in three dimensions for cylindrical coordinates $(r, z, \phi)$. But in the analysis of ducts with circular cross-section, which is the case of ground loop heat exchanger, the heat equation is reduced to the radial dimension, *r*, as the variation in axial direction is neglected. The equation for the thermal process becomes:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}. \tag{4}$$

The boundary conditions to the ground loop heat exchanger are: prescribed surface temperature, prescribed flux and heat flow proportional to the temperature difference over a surface thermal resistance. Though the temperature of the borehole and the ground varies in the vertical direction, an average value is taken for the entire length of the borehole, neglecting the vertical effects.

If the power $q_1$ is injected, starting when $t$=0 and the temperature of the rock is zero, then at time *t* the temperature will be:

$$T_q(r,t) = \frac{1}{4\pi\lambda}\int_0^t \Phi(t')e^{-r^2/4a(t-t')}\,\frac{dt'}{t-t'}. \tag{5}$$

$\Phi(t') = q$ and constant gives:

$$T_q(r,t) = \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4at}}^{\infty}\frac{1}{s}\,e^{-s}ds = \frac{q}{4\pi\lambda}E_1\left(\frac{r^2}{4\alpha t}\right), \tag{6}$$

$$\text{where } \int_{\frac{r^2}{4at}}^{\infty}\frac{1}{s}\,e^{-s}ds = E_1\left(\frac{r^2}{4at}\right). \tag{7}$$

Here, $E_1$ is called the exponential integral. For large values of the non-dimensional time $\alpha t/r^2$ the exponential integral can be approximated by the following relation:

$$E_1\left(\frac{r^2}{4\alpha t}\right) = \ln\left(\frac{4\alpha t}{r^2}\right) - \gamma - \frac{1}{4}\left[\frac{r^2}{\alpha t} - \left(\frac{r^2}{4\alpha t}\right)^2\right] \qquad \frac{\alpha t}{r^2} \geq 0.5 \tag{8}$$

This can be further approximated by this simple and useful correlation:

$$E_t\left(\frac{at}{r^2}\right) \approx \ln\left(\frac{4at}{r^2}\right) - \gamma \qquad \frac{\alpha t}{r^2} \geq 5, \tag{9}$$

where γ=0.577722… is Euler's constant. This is valid when the thermal process in the region within the radius *r* reaches steady state, when the maximum error is 2% for $\alpha t/r^2 \geq 5$.

We are interested about connection between the undisturbed ground temperature, $T_0$, and the temperature of the heat carrier fluid, $T_f$: When the heat first is extracted or injected into a borehole a transient process starts. The connection between the different parameters involved is shown in the following equation:

$$T_f = \pm\frac{\Phi}{4\pi\lambda H}\left[\ln\left(\frac{4at}{r^2}\right) - \gamma\right] - \frac{R_b\Phi}{H} + T_0, \tag{10}$$

$$\text{for } t \geq \frac{5r_b^2}{a}. \tag{11}$$

After a certain time ($t_b$) the transient process ends and the conditions become stationary:

$$t_b = \frac{H^2}{9a}. \tag{12}$$

The following equation describes the connection between the parameters during stationary conditions:

$$T_f - T_0 = \pm\frac{\Phi}{H}\left[\frac{1}{2\pi\lambda}\ln\left(\frac{H}{2r}\right) \pm R_b\right] \tag{13}$$

+ extracted heat

- injected heat.

$R_b$ is the fluid to ground thermal resistance. This resistance is a measure of all borehole elements including grout resistance and resistance due to convection and conduction in the pipe [6].

## 2.3 Numerical analysis of finite line-source model

The theoretical basis for the single U-tube, multiple borehole ground-loop heat exchanger models comes from the work of Eskilson [7]. His approach to the problem of determining the temperature distribution around a borehole is a hybrid model combining analytical and numerical solution techniques. A two dimensional numerical calculation is made using transient finite-difference equations on a radial-axial coordinate system for a single borehole in homogeneous ground with constant initial and boundary condition. The thermal capacitance and thermal resistance of the individual borehole elements are neglected in Eskilson's model. The temperature fields from a single borehole are superimposed in space to obtain the response from a borehole field of several boreholes in certain arrangement.

The temperature response of the borehole field is converted to a set of non-dimensional temperature response factors, called g-functions. The g-function allows the calculation of the temperature change at the borehole wall in response to a step heat input. Once the response of the borehole field to a single step heat pulse is represented with a g-function, the response to any arbitrary heat rejection/extraction function can be determined by devolving the heat rejection/extraction into a series of step functions, and superimposing the response to each step function. Eskilson has calculated g-functions (data sets) for a wide variety of borehole configurations [8, 9].

Fig.2 shows the temperature response factor curves (g-functions) plotted versus non-dimensional time for various multiple borehole configurations and compares them to the temperature response factor curve for a single borehole. The g-functions in Fig.2 correspond to borehole configurations with fixed ratio of 0.1 between the borehole spacing and the borehole depth. The thermal interaction between the boreholes is stronger as the number of boreholes in the field is increased. The interaction increases as time of operation increases.

The detailed numerical model used by Eskilson developing the g-function approximates the borehole as a line-source with finite length, so that the borehole end effects can be considered. This approximation is only valid for times longer than $t \geq \frac{5r_b^2}{a}$, since the transient process in the borehole must be considered for shorter period. For a typical borehole, this value can be in the order of 3 to 6 hours.

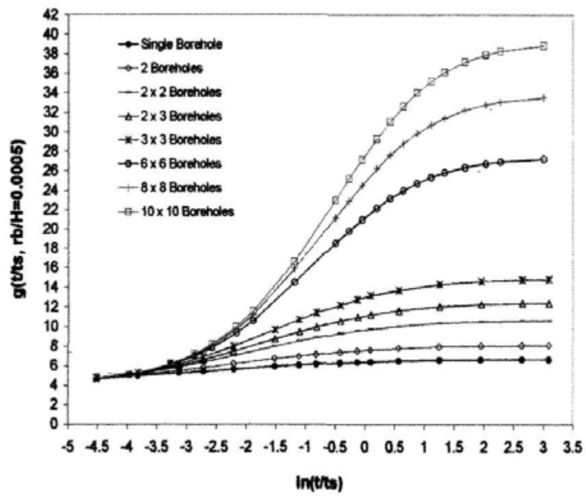


Fig.2: Temperature response factors (g-functions) for various multiple borehole configurations compared to the temperature response curve for a single borehole.

Non-dimensional temperature drop g is in this model can be written as:

$$g(E_s, \frac{r_b}{H}) = \frac{\Delta T 2\pi\lambda}{q}. \tag{14}$$

The non-dimensional temperature response g (concept introduced by Eskilson) is defined as a function of non-dimensional time $(E_s)$ and non-dimensional radius of borehole $r_b/H$. For individual borehole the g function within the interval $5\,r_b^2/a < t < t_s$ can be written as approximation:

$$g\left(E_s, \frac{r_b}{H}\right) = \ln\left(\frac{H}{2r_b}\right) + 0.5\ln(E_s). \tag{15}$$

For times, longer than $t$, the individual borehole come near thermal balance after a function:

$$g\left(\frac{r_b}{H}\right) = \ln\left(\frac{H}{2r_b}\right). \tag{16}$$

Temperature of hole $(T_b)$ on a radius $(r_1)$ of borehole is:

$$T_b = T_0 - \frac{q}{2\pi\lambda_z} g\left(E_s, \frac{r_b}{H}\right). \quad (17)$$

This equation is valid only in the neighborhood of a borehole and makes possible to determine the temperature behavior in the entire surrounding of borehole with a single response function.

Non-dimensional g-function is not dependent only on Eskilson's number and non-dimensional radius of borehole. It is dependent from position of borehole, distance between boreholes and from radius of boreholes. The last dependence is very simple:

$$g\left(E_s, \frac{r_1}{H}\right) = \ln\left(E_s, \frac{r_b}{H}\right) - \ln\left(\frac{r_1}{r_b}\right). \quad (18)$$

Numerical model used by Eskilson is very retardate and this model is difficult to include directly in programs for planning and energy analyzing practical applications, where the calculated g-function needs to be recalculated for different configurations of boreholes. Beside that, this model is too sensitive for changes in dimension of individual boreholes and on interacting configuration of boreholes.

We can solve this problem in the order of minutes with analytical solution of model finite line-source.

## 2.4 Analytical solution of finite line-source model

Like in the most models, which analyses thermal occurrences between ground and borehole, there is a need to adopt some simplifications [10, 11]:

- The ground is regarded as homogeneous and semi-infinite medium.
- The heat transfer along the borehole axis is neglected. Then the problem may be simplified as two-dimensional.
- The borehole is approximated by a line heat source.
- The medium has a uniform initial temperature ($T_0$).
- The heating rate per length of the source ($q$) is constant.

The temperature rise in the infinite medium is in some moment, because of this pointed source, defined as:

$$dT = \frac{qdh}{4\pi\lambda} \cdot \frac{erfc\left(\frac{\sqrt{r^2 + (z-h)^2}}{2\sqrt{at}}\right)}{\sqrt{r^2 + (z-h)^2}}, \quad (19)$$

where

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \ . \quad (20)$$

The temperature rise is, because of finite line-source, obtained with integration of contributions of all pointed sources:

$$T(r,z,t) - T_0 = \frac{qdh}{4\pi\lambda} \int_0^H \left[ \frac{erfc\left(\frac{\sqrt{r^2 + (z-h)^2}}{2\sqrt{at}}\right)}{\sqrt{r^2 + (z-h)^2}} - \frac{erfc\left(\frac{\sqrt{r^2 + (z+h)^2}}{2\sqrt{at}}\right)}{\sqrt{r^2 + (z+h)^2}} \right] dh \quad (21)$$

Temperature of borehole wall, where $r = r_b$, changes with time and with depth. Usually the temperature on half of depth ($z$ = $H$/2) is taken as representational temperature of borehole. If we follow the definition at Eskilson accession, the g-function is obtained for individual borehole:

$$g\left(\frac{at}{H^2}, \frac{r}{H}\right) = \frac{2\pi\lambda[T(r, 0.5H, t) - T_0]}{q} \quad (22)$$

$$g\left(\frac{at}{H^2}, \frac{r}{H}\right) = -\frac{1}{2} \int_0^1 \left[ \frac{erfc\left(\frac{\sqrt{\left(\frac{r}{H}\right)^2 + \left(0.5 - \frac{h}{H}\right)^2}}{2\sqrt{\frac{at}{H^2}}}\right)}{\sqrt{\left(\frac{r}{H}\right)^2 + \left(0.5 - \frac{h}{H}\right)^2}} - \frac{erfc\left(\frac{\sqrt{\left(\frac{r}{H}\right)^2 + \left(0.5 + \frac{h}{H}\right)^2}}{2\sqrt{\frac{at}{H^2}}}\right)}{\sqrt{\left(\frac{r}{H}\right)^2 + \left(0.5 + \frac{h}{H}\right)^2}} \right] d\left(\frac{h}{H}\right). \quad (23)$$

The obtained temperature response to a single line-source heating or cooling can be used to compute the response of a GHE with multiple boreholes by superimposition of all temperature rises caused by individual boreholes. Preference of this model before Eskilson's is that, that the integral in equation (23) can be solved with computer help very quickly and simple. A second good side of analytical solution is fact, that the temperature around more boreholes can be calculated in a very short time with suitable choice of parameters, in the meantime where Eskilson's g-function are calculated for exactly defined configurations.

## 2.5 Heat conduction outside boreholes

In GHEs the borehole diameter is much smaller compared to their depth, and the ground can be treated as a semi-infinite medium. Then, the one-dimensional line source model in infinite medium is often used in GHE analysis, often referred to as Kelvin's model. While being simple, this model is inadequate for analysis of long-term performance of the GHEs. In many GCHP applications the heating loads are not in balance with the cooling loads in a year round basis. In case that the heat injected in summer cannot be extracted in winter, the redundant heat will accumulate in the ground and thus lead to increase in the annual mean temperature in adjacent soil. With the effect of the heat transfer on the ground surface taken into account, the influence of the imbalanced heat will approach a relatively steady state after the ground heat exchanger operates for a long enough period. This process normally takes ten years or even more, depending mainly on the depth of the boreholes. The variation in the annual mean temperature of the ambient soil around the GHE will affect its long-term behavior; and thus it must be taken into account when the ground loop is designed.

The transient heat conduction around boreholes of the GHEs can be also analyzed in a two-dimensional model. An analytical solution of the transient temperature response has been derived in a semi-infinite medium with a line-source of finite length. This solution is suitable for sizing the ground loop of GCHP systems because it describes the GHE performance more adequately than the 1-D model does with an infinite line-source. The 2-D model assumes that the ground is regarded as a homogeneous semi-infinite medium with a uniform initial temperature, and that a line-source stretching vertically from the boundary to a certain depth, $H$, releases heat at a constant rate per length, $q$. due to the central symmetry of the problem the temperature distribution is two-dimensional in the cylindrical coordinates [11].

## 2.6 Dimensioning of an underground thermal energy system

When dimensioning an energy well one often starts with a given heat injection rate (or, as the case often is, a heat extraction rate) that varies over the year. There is also a limit for how high (or low) the temperature is allowed to become in the borehole. Several parameters decide how the ground (bedrock) temperature is affected by heat extraction/injection in a borehole. From the equations of heat conduction we realize that the following properties have to be known if we know the heat extraction/injection rate:

- Ground properties (thermal conductivity, thermal capacity, undisturbed ground mean temperature),
- Borehole properties (depth, radius),
- Heat exchanger properties (thermal resistance between heat carrier fluid and borehole wall).

There are, however, several parameters that can not be seen in equations of heat conduction. Some of the properties mentioned above are dependent of other parameters. The thermal resistance, for example, is a complex factor that considerably with the design of heat exchanger. Some other properties are left out of account by the equations because they are assumed not to exist or to have a negligible influence. Some properties that are not seen in the equations of thermal conduction are:

- Ground properties (conditions on the ground surface, geothermal gradient, other physical properties, i.e. groundwater conditions and cracks),
- Borehole properties (thermal insulation of the upper part of the borehole),
- Heat exchanger properties (type of borehole filling, pipe properties (type, radius, wall thickness, thermal conductivity), heat carrier fluid properties (thermal conductivity, thermal capacity, density, viscosity, freezing point, flow rate, state of flow)),
- Miscellaneous (convection) [12].

## 3 Response functions and thermal influence between boreholes

First, the analytical solution of g -functions is compared with numerical solution. The data used for the calculation of analytical g-functions are:

- efficient depth of borehole $H$ = 100 m,
- ground thermal diffusivity $a = 1{,}62\times10^{-6}$ m$^2$/s,
- thermal conductivity of rock $\lambda$ = 3.5 W/mK,
- heat capacity of rock $c$ = 900 J/kgK,
- density of rock $\rho$ = 2400 kg/m$^3$,
- Heat extraction rate per meter $q$ = 22 W/m,
- borehole diameter $2r_b$ = 0.11m,
- annual mean temperature of ground surface $T_0$ = 8 ºC,
- break time for time criteria $t_s$ = 26 years,
- time $t$:
  - $t_1$ = 1.3 years → $ln(t/t_s)$ = -3,
  - $t_2$ = 26 years → $ln(t/t_s)$ = 0,
  - $t_3$ = 520 years → $ln(t/t_s)$ = 3,
- borehole spacing $B$:
  - $B_1$ = 5.5 m → $B/H$ = 0.05,
  - $B_2$ = 11 m → $B/H$ = 0.1,
  - $B_3$ = 33 m → $B/H$ = 0.3.

Analytical g-functions are calculated after equation (23). For a borehole field of varying configurations its temperature response and thermal influence between boreholes can be determined by the superposition principle. Fig.3, Fig.4 and Fig.5 show the temperature response factors curves (g-functions) plotted versus non-dimensional time, where $t$ is the time in seconds and $t_s$ is the time scale. The g-functions are plotted for a single $r_b/H$ ratio, where $r_b$ is the borehole radius and $H$ the borehole depth, and for a different $B/H$ ratio, where $B$ is the borehole spacing. In Fig.3, Fig.4 and Fig.5 numerical g-functions are compared with analytical g-functions [12].

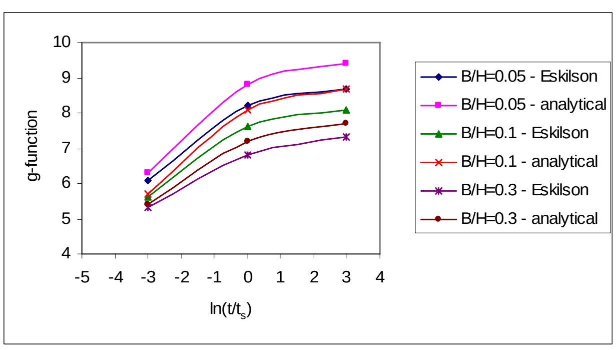


Fig.3: Temperature response factors (g-functions) for 1x2 borehole configurations.

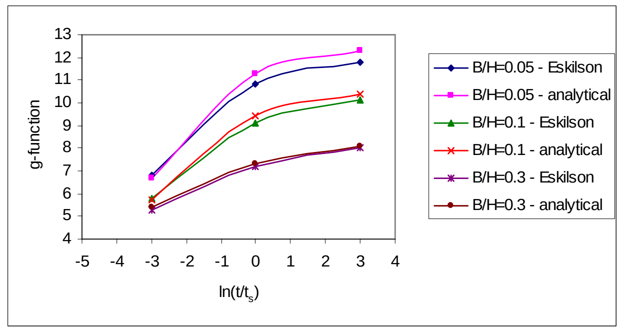


Fig.4: Temperature response factors (g-functions) for 1x4 (four sequence boreholes) borehole configurations.

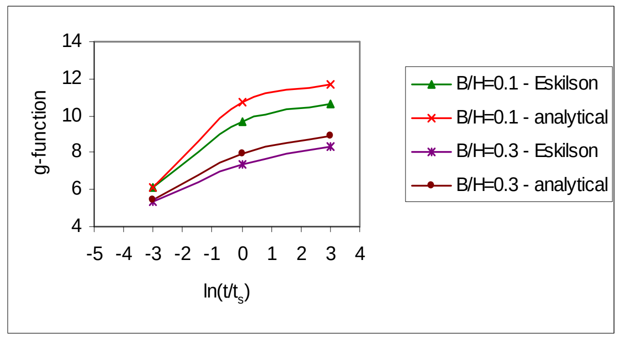


Fig.5: Temperature response factors (g-functions) for 2x2 (four quadratic arranged boreholes) borehole configurations.

Values, which were obtained with analytical method, are in all cases higher as numerical, but they do not differentiate for more than 7 % except in case of 2x2 borehole configurations, where the difference is around 12 %. It also can be found out that differences rise with time and these shows, that short-term influence between boreholes is unimportant. Comparison between Fig.3 and Fig.4 shows that g-functions for four boreholes have similar course as than for two boreholes. In case of 1x4 boreholes, the g-functions are sensitively higher, because there are summarizing contributions interacting influence of four boreholes. Differences between g-functions in stationary state are also higher than in 1x2 boreholes, which means, that at four sequence boreholes spacing between boreholes has yet higher influence on interacting temperature activity. In case of 2x2 (four quadratic arranged boreholes) boreholes the spacing 5 m between boreholes is too small, because the thermal influence is too high. Here, the distance has even higher influence on temperature changes in ground than in case of 1x4 boreholes. On the basis of analytical g-functions and given parameters, the changes of temperature field in the surrounding of boreholes can be determined. Non-dimensional temperature drop increasing with reducing spacing between boreholes and with time. From Fig.3, Fig.4 and Fig.5 can be seen that the g-functions rise rapidly at the early period of heating, and then, turn to a rather gentle increase. Finally g-functions reach a steady state when the time approaches infinity.

This paper also represent the changes of temperature field, when the heat is extracted (in winter) from ground. Heat is extracted constantly at the same rate *q* throughout the years.

Fig.6 to Fig.12 shows the results of temperature field analyze in the surrounding of boreholes. The temperature gradient in the surrounding of boreholes is much higher then at larger distance. Presuming the changes of temperature profile in the next 520 years will be very small, the stationary state is achieved after 26 years. Temperature drop in surrounding is in case of larger spacing between boreholes smaller, other characteristics of temperature field are the same. This is in accordance with g-functions, which have the similar form at a different spacing between the boreholes. Thermal influence between boreholes for the first years of operation is not observable. It becomes observable with longer operation time.

In Fig.6 are present the results of temperature field analyze in the surrounding of both boreholes and for spacing between boreholes is 5.5 m. Temperature profile presents that after 1.3 years the borehole wall temperature fall on 1.8 ºC, but the stationary state is not achieved. The stationary state is achieved after 26 years, because the temperature profile change very small in the next 520 years.

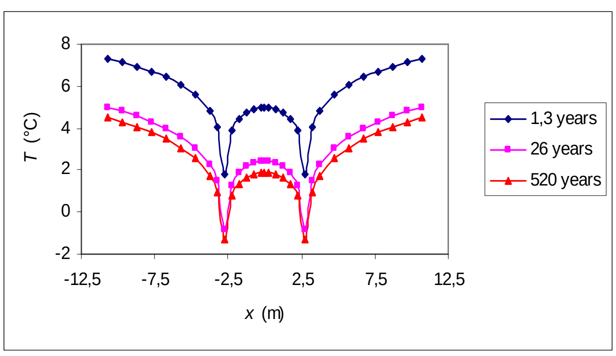


Fig.6: Ground temperature in the depth of 55 m in dependence of spacing between two boreholes (1x2) *B* = 5.5 m and time. Boreholes are placed in *x* = -2.75 m and *x* = 2.75 m.

From Fig.7 we can see that the thermal influence between both boreholes is still important, because the borehole wall temperature fall under 0 ºC as early as 26 years. The temperature drop in surrounding is in this case smaller than in the first case (Fig.6).

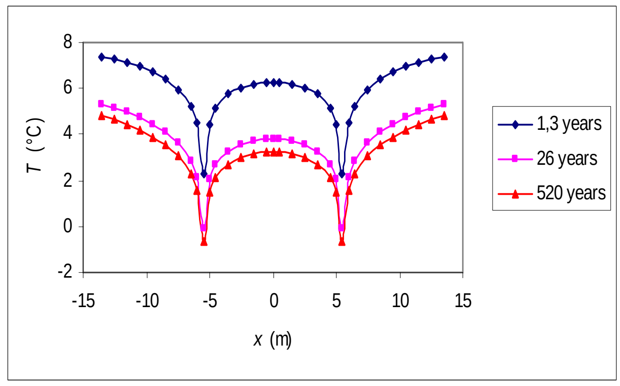


Fig.7: Ground temperature in the depth of 55 m in dependence of spacing between two boreholes (1x2) *B* = 11 m and time.
Boreholes are placed in *x* = -5.5 m and *x* = 5.5 m.

Fig.8 shows temperature field for two boreholes, which are mutual distant 33 m. The difference between borehole wall temperature after 1.3 years and after 520 years are very small, approximate 2.3 ºC. The temperature influence is in this case small.

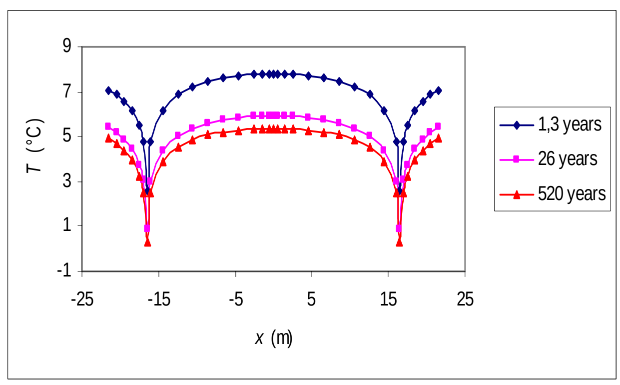


Fig.8: Ground temperature in the depth of 55 m in dependence of spacing between two boreholes (1x2) *B* = 33 m and time.
Boreholes are placed in *x* = -16.5 m and *x* = 16.5 m.

From Fig.9 is evident that the consequence of small distance between 1x4 sequence patterns is rather large temperature drop in surrounding the boreholes. Stationary state is achieved after 26 years. The temperature gradient in boreholes nearness is higher than in more faraway places. This was also being seen at two boreholes. The borehole wall temperature of two central boreholes is after

1.3 years of operation almost 0 ºC and after 26 years -4.4 ºC. The select spacing between single boreholes (5.5 m) is by this number of boreholes to small, because the temperature field in boreholes surrounding change heavy in relative short time.

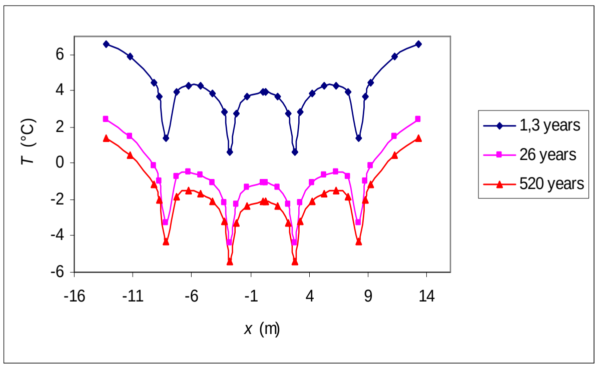


Fig.9: Ground temperature in the depth of 55 m in dependence of spacing between four boreholes (1x4) *B* = 5.5 m and time. Boreholes are placed in *x* = -8.25 m, *x* = -2.75 m, x = 2.75 m and x = 8.25 m.

Fig.10 present ground temperature if the spacing between boreholes enlarges on 11 m. While after 1.3 years the drop of borehole wall temperature is approximate the same, with longer operation time the temperature decrease in central two boreholes. From this we can make inferences that in the first years of operation the temperature influence is not observed, while with longer time operation the temperature influence increase and become much visible.

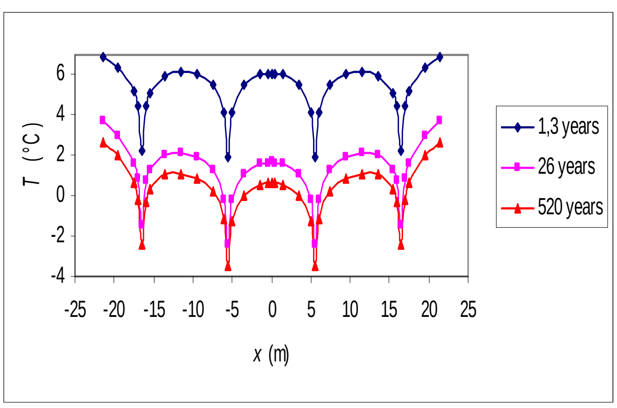


Fig.10: Ground temperature in the depth of 55 m in dependence of spacing between four boreholes (1x4) *B* = 11 m and time. Boreholes are placed in *x* = -16.5 m, *x* = -5.5 m, x = 5.5 m and x = 16.5 m.

Fig.11 shows temperature field for four boreholes with 33 m spacing between boreholes. The temperature influence between individual boreholes is small, because the change of ground temperature is higher only in direct borehole nearness, while in the higher distance the ground temperature is above 0 ºC after 520 years of operation.

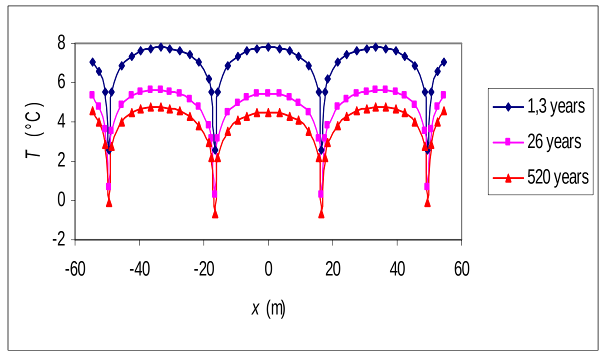


Fig.11: Ground temperature in the depth of 55 m in dependence of spacing between four boreholes (1x4) *B* = 33 m and time. Boreholes are placed in *x* = -49.5 m, *x* = -16.5 m, x = 16.5 m and x = 49.5 m.

In Fig.12 is present 3-D temperature field in surrounding of four quadratic arranged boreholes. Along the individual boreholes wall the temperature fall on -4 ºC, while in their surrounding the temperature drop is smaller. In the ground between boreholes the temperature range around 0 ºC, while the temperature range between 1 and 2 ºC in the edge. In long-term the changes in ground temperature at this mutual boreholes distance are much high and for this reason is better to choose higher distance between boreholes if that is possible.

The net heating or cooling of the ground over each season clearly depends on the accumulated heat rejection and extraction, and therefore on the building loads throughout the whole year. It also depends on the depth, number and configuration of the boreholes. It is important that the design methodology account for thermal interactions between the boreholes and with the far field. Any design methodology has to be based then on the building loads calculated throughout the whole year, not just the peak heating and cooling loads. Annual and multiyear simulation consequently becomes an invaluable tool in the design and energy analysis of such systems – both in terms of calculating annual building loads, and long-term ground thermal response.

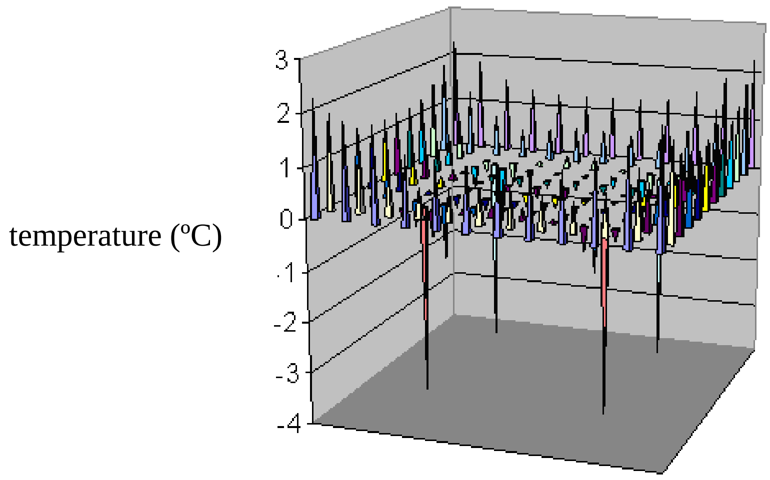


Fig.12: Temperature field after 520 years in surrounding of four quadratic arranged boreholes. Spacing between boreholes is 11 m, size of field is 21 m x 21 m.

## 4 Conclusions

The choice of number of boreholes, their configuration and precise position of individual borehole is very important, because that defines the response functions and their long-term interacting influence. It is observed that the analytical solution follows the numerical results very well. Although the analytical expressions look rather complicated, these functions are easily calculated with computer. It is clearly shown in the figures that the g-functions converted from the line source response factors (analytical g-functions) are greater then the g – function obtained with numerical model derived from the work of Eskilson. Greater g-functions mean higher temperature at borehole wall.

On the basis of g-functions and present parameters the change of temperature field can be evaluated in the surrounding of boreholes. The results show that the change of temperature field is dependent on spacing between boreholes. This thermal influence between boreholes is almost imperceptible in the start of operation, but it becomes higher with time until the stationary state is not achieved. Thermal influence between boreholes decreases with increasing the spacing between boreholes and become negligible, if the spacing is larger then length of borehole. Because of that it is important that with the exact calculation the setting of borehole is defined so, that the thermal influence between them is minimized. By this we decrease operational cost of heat pump and extend the time of their optimal exploitation.

Work is now underway to study how the ground temperature changes, when the heat is rejected (in summer) in the ground. We also study how the ground temperature changes, when the heat load is not constantly extracted or injected throughout the years. We will consider different load profiles, such as pulsated extraction (heat is alternately extract and inject every day of the year), periodic extraction (heat extraction or injection is base on a sinusoidal function) and composite extraction (the total heat extraction or injection rate is obtain by superposition of the constant rate, periodic rate and pulsated load).

*Nomenclature*:

$T_f$ working fluid average temperature (ºC)
$\Phi$ heat injection/extraction rate (W)
$q$ heat injection/extraction per unit length of borehole (W/m)
$\lambda$ thermal conductivity (W/m K)
$H$ borehole depth (m)
$a$ ground thermal diffusivity ($m^2/s$)
$t$ time (s)
$r$ radius (m)
$\gamma$ Euler constant (=0,5772)
$R_b$ thermal resistance in the borehole (m K/W)
$T_0$ ground temperature (ºC)
$r_b$ borehole radius (m)
$t_b$ break time for time criteria (s)
$E_s$ non-dimensional time
$t_s$ reference time borehole analysis (s)
$g$ non-dimensional temperature response factor
$T_b$ temperature of hole (ºC)
$h$ variable of the depth of borehole (m)

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