# FIELD MEASUREMENTS AND MODELLING OF HEAT TRANSFER. CHARACTERISTICS OF GROUND HEAT EXCHANGERS

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**Abstract.** A number of parameters and characteristics of geological formations have a major influence on the long-term performance of ground heat exchangers. Some of these parameters can be measured, others in the laboratory and their evolution over time can be modelled using dedicated software. One of the commonly used software is EED (Earth Energy Designer) which can model, based on characteristics measured in the field and/or laboratory, the evolution over time of the temperature taken from geological formations, the evolution of loads, cooling, heating versus load introduced/extracted from geological formations over certain periods of time.

**Keywords:** geothermal energy, geo heat exchangers, heat pumps, rock heat transfer.

**Rezumat. Măsurători pe teren și modelarea transferului de căldură. Caracteristicile geoschimbătoarelor de căldură**. O serie de parametri și caracteristici ale formațiunilor geologice influențează major performanțele geoschimbătoarelor de căldură pe termen lung. Unii dintre acești parametri se pot măsura în situ, alții în laborator iar evoluția lor în timp se poate modela cu ajutorul unor softuri dedicate. Unul dintre softurile folosite frecvent este EED (Earth Energy Designer) care poate modela, pe baza unor caracterici măsurate în teren și/sau laborator, evoluția în timp a temperaturii preluate din formațiunile geologice, evoluția sarcinilor, de răcire, încălzire față de sarcina introdusă/extrasă din formațiunile geologice pe anumite perioade de timp.

**Cuvinte cheie:** Geoschimbătoare de căldură, pompe de căldură, transfer termic prin roci.

## INTRODUCTION

Geological formations have certain thermal and physical characteristics that make them a desirable source for geothermal heat pumps. Some of these can be measured directly while others can be determined by laboratory analysis or both. Cof these properties are to the true values, more efficiently can systems be designed without being over or underestimated.

It should be noted that practically all geological formations are suitable for geothermal energy, but it is important that the costs of installing these systems are not so high as to increase the payback time of the investment unduly. At the moment, for example, if we are talking about geological formations with predominantly sedimentary rocks, the drilling costs range from 35 EUR/m to 55 EUR/m using wet drilling type, whereas drilling in geological formations with hard and very hard rocks; magmatic or metamorphic ones, which can only be done with dry drilling, possibly using sonic drilling, can double or even triple the drilling costs.

In fact, of all the systems based on heat pumps, the ground heat exchangers part is the most expensive. For this reason, it is extremely important to have data as reliable as possible about the geological formations that will host the ground heat exchanger.

## THERMAL AND PHYSICAL PROPERTIES OF ROCKS

The ability of geological formations to transmit and absorb heat energy is influenced by the following thermo-physical properties:

- thermal conductivity;
- temperature
- thermal resistivity;
- specific heat, heat capacity;
- thermal diffusivity;
- heat flow;
- geothermal flow;
- geothermal gradient.

The law of heat conduction or Fourier's law underlies the determination of all these properties. According to it the heat flux density **qi**, the specific energy flow vector are defined as the product of the tensor **λi** of thermal conductivity - λ, and the temperature gradient vector **∂T/∂x**, according to the relation:

$$q_i = -\lambda i \frac{\partial T}{\partial X_i} \qquad \textbf{1.}$$

Thermal conductivity - **λ** - can be considered the most important thermal property of rocks especially for the field of geothermal energy extraction and its use in heat pump systems. It illustrates the property of media to transmit thermal energy. It expresses the amount of heat - **Q** - that is transmitted in a time - **τ -** through a body of cross-section -

**s** - and length - **l** - whose opposite sides are at temperatures - $\mathbf{t_1}$ - and respectively - $\mathbf{t_2}$ (ASAAD, Y. 1955, BUNTEBARTH G. 1991):

$$\lambda = Q / [(T_2 - T_1) \cdot s / l \cdot \tau] \quad [W/m \cdot K] \qquad \textbf{2.}$$

**Q** - the amount of heat transmitted through the body [J]
**s** - cross-section of the body under consideration [m2]
**l** - length of the body under consideration [m]
$T_1$, $T_2$ - the temperatures of each face of the body under consideration [K]
$\tau$ - time [s]
$q = \lambda Gt$

Based on the above relation, the thermal conductivity of the medium is the ratio of heat flux to temperature gradient (Gt). Both the thermal conductivity and the geothermal gradient are not constant quantities but vary widely as a result of the variation of the factors that influence them; the lithology of the formations crossed, the contribution of thermal energy from deep areas, etc. As a result, the thermal flux will also be estimated and not the real one because it is almost impossible to calculate it exactly. The most commonly used methods of determination are the interval method and the Bullard method. The interval method is used when there are a sufficiently large number of measurements per depth so that both thermal conductivity and thermal gradient can be considered to be constant. For each interval the heat flux will be calculated as the product of the thermal conductivity and the geothermal gradient.

Thermal conductivity can be considered approximately isotropic for many rock types, such as volcanic and plutonic rocks. In conclusion the heat flow will manifest itself mainly in the vertical plane so only the vertical component can be considered. The thermal conductivity of sedimentary and metamorphic rocks is strongly anisotropic and as such the lateral heat flow will be dominant as value. In conclusion, in the case of these rocks, detailed information on anisotropy is needed which requires complex laboratory measurements.

The conductivity increases with decreasing rock grain size because the number of contacts between the grains that make up the rock increases along the heat flow propagation path. Also important in sedimentary rocks are the quantity, composition and structure of the cement: clay cement has a lower thermal conductivity than carbonate or siliceous cement.

It depends on the nature of the contained fluid (water with different degrees of mineralization, oil, gas) and its distribution in the rock. The thermal conductivity of water-saturated rock is higher than that of oil-saturated rock, and that of gas-saturated rock is much lower than that of the same rock saturated with water or oil.

There are a number of instruments that can determine thermal conductivity in situ, directly and indirectly. One of these is a device that can extract samples up to 120 cm thick, but there are also auxiliary devices that can collect multiple samples that can be examined directly in the field immediately after extraction or sent to a laboratory. The data logger on the plant can provide data both graphically and numerically expressed in W/mK. The data is stored in the device's internal memory – Fig. 1.


Figure 1. Device for measuring thermal conductivity in situ.

The thermal conductivity measured in situ has a higher accuracy than the one obtained in the laboratory, even though the other one also takes into account the effect of temperature, pressure and pore fluid. The reason for the difference in value between the two methods is the dependence on a certain range in which different aspects are involved. The values of this parameter recorded the closest to reality because in this case the rocks are usually not disturbed their natural state, whereas small scale variations can be missed by laboratory measurements as is the case for conductivity variations due to the anisotropy of mineral structure.

There are a multitude of machines that determine somewhat indirectly an average value of thermal conductivity, but we should be careful, this value does not actually represent the thermal conductivity of the geological formations but an average value between the thermal conductivity of the rocks, that of the wall of the transport pipe and that of the fluid transporting the energy, basically a horizontal and a vertical average value. As the name suggests, these devices measure the thermal response of geological formations. Basically, they all do pretty much the same thing, the choice being made affinity for one manufacturer or another and obviously the price of such equipment. The more sophisticated ones have the advantage of better memory for data acquisition and software that saves you from doing calculations.

The main elements of such equipment are as follows (Fig. 2):

- circulation pump;
- 4 electric resistance plunger-type heaters of a certain capacity (1500 W each), mounted in a steel jacket. Each of these heaters can be connected separately to the power supply;
- 4 thermal protection relays (60 ºC) which are interposed on the circuit;
- 5 one expansion vessel, equipped with membrane, overpressure safety valve (3 bar), automatic deaerator, taps;
- 2 water circuit inlets and outlets;
- an electrical control box;
- electrical ON/OFF switches for the circulation pump and for each of the four heaters;
- the connectors for all the sensors in the measurement scheme, which will be connected to the Data Logger;
- 2 PT 1000 temperature sensors with connectors.
- 4 high temperature protection relays (60 ºC).
- grounding circuit.

More advanced devices can also capture data from any temperature sensors placed in the ground. We can also determine the thermal conductivity of rocks experimentally. The determination methods are based on solving the thermal conductivity equation and can be: transient measurement methods and steady-state measurement methods (ZHANG et al., 2018).


Legend

1 - Housing
2 - Thermal agent stub outlet
3 - Thermal agent stub input
4 - Vertical column
5 - Circulating pump
6 - Bollard box
7 - Electrical resistances

Figure 2. Manufactured equipment for measuring the thermal response of geological formations.

More advanced devices can also capture data from any temperature sensors in the ground.

The record of the values measured by the TRTFG equipment goes to a data logger. The choice of the data logger depends on the data acquisition capacity and price. For the study of the presented equipment, a data logger type COMET S 0121 was used which has the possibility to store several types of data

The equipment is designed to measure and record temperatures from temperature probes connected via connectors that attach to the data logger. Temperature values are read every 20 seconds and recorded in the internal non-volatile memory. The logger is then connected via a USB adapter cable to a laptop, which is used to power up and set the parameters. Dedicated software allows data transfer; 26,000 measurements (temperatures) in text format or tables that can be processed in Excel.

The thermal conductivity of rocks can be estimated by knowing their mineral content, as they have a well-defined composition and show much less variation in thermal conductivity than rocks. In order to know the thermal conductivity of a porous rock as a whole, the different saturating fluids that fill the pores must be known, which can be used when opting for laboratory measurements (DEMONGODIN et al., 1991).

For metamorphic rocks and analogously for plutonic rocks, the decrease in thermal conductivity with temperature is dependent on the dominant mineral phase content.

Often, thermal conductivity data are only available for room temperature, which obviously almost never corresponds to the temperature of geological formations, so attempts are made to calculate them using empirical formulas proposed for extrapolation, based on data obtained from measurements at elevated temperatures.

Thermal resistivity is the inverse of thermal conductivity.

Specific heat - c is the amount of heat required to raise the temperature of one gram of a substance by 1°C. It represents the property of media to accumulate heat energy. It is expressed in J/KgK. The specific heat of different types of rock is almost uniform at room temperature. The specific heat multiplied by the density gives the heat capacity of the substance under consideration.

Thermal diffusivity - **a** (m2/s) - is the areal propagation velocity of a thermal disturbance (the surface area over which a thermal disturbance propagates in unit time) and is expressed quantitatively in terms of the ratio of the

$$\mathbf{a=\lambda/c\cdot\rho} \qquad \mathbf{3.}$$

where: ρ - density of the medium.
λ - conductivity

Thermal diffusivity can illustrate the degree of disturbance of natural geothermal conditions during drilling of a well and the time to restore the initial thermal regime. It can be assessed by thermal measurements in a non-stationary regime. The best calculation method is using the above formula.

Heat flow - f - at any point in a homogeneous and isotropic medium is defined as a vector:

$$\mathbf{f} = \frac{-\lambda\Delta t}{l} \qquad \mathbf{4.}$$

where:
t - temperature,
λ - thermal conductivity,
l - length
The minus sign indicates that the heat flow is considered to be transmitted, through any isothermal surface, from inside to outside, from higher to lower temperature.
Heat flow - the amount of heat transferred (through a body or between two bodies) in a unit of time.

$$\boldsymbol{Q = \frac{dq}{dt}} \qquad \mathbf{5.}$$

**Unit heat flow** - the heat flow in relation to the isothermal unit area (GEHLIN & HELLSTROM, 2002).

$$\boldsymbol{q = \frac{dQ}{dS}} \qquad \left[\boldsymbol{W}/_{\boldsymbol{m^2}}\right] \qquad \mathbf{6.}$$

**S -** the elementary surface on which the flow falls normally.

The area is considered to be oriented along the direction of the normal, hence the heat flux is a vector quantity.

The unit heat flux propagates from the temperature isotherm **- T + δT -** to the temperature isotherm **- T,** along the path of least propagation resistance, in the normal direction. The thermal gradient has the same direction and opposite direction.

Thermal conduction - is the process of heat transfer within a body or between solid bodies in contact, from the higher temperature zone to the lower temperature zone. The fundamental equation of conduction resulting from Fourier's law is:

$$Q = -\lambda S\frac{dT}{dx} \qquad [\boldsymbol{W}] \qquad \mathbf{7.}$$

$$q_s = -\lambda\, grad\, dT \qquad \mathbf{8.}$$

T- fluid temperature [K]
$q_s$ - unit heat flux [W/m$^2$]
S - surface area [m$^2$]

**Geothermal flow** - q - is the heat flow propagating from the Earth's interior to the surface in the vertical direction. It is defined by the relation (BULLARD & NIBLETT,1951; DAVIS, 1988):

$$q = -\lambda\left(\partial T/_{\partial z}\right) \qquad \mathbf{9}.$$

The oceanic lithosphere is relatively uniform in composition and a small amount of heat is generated within it by radioactivity. The flow of heat in the oceanic lithosphere essentially varies with the age of the formations.

The continental lithosphere, however, is quite heterogeneous in composition, mainly due to its tectonic activity. Heat flow depends on the production of radioactive heat in the crust.

As such the continental heat flow:

- is proportional to the radioactivity of the crustal surface in a given region;
- decreases with time since the last major tectonic event.

Table 1 shows some of the important geothermal parameters for determining the size of the geothermal heat exchanger.

Table 1. Geothermal parameters (Heat Flow of the Earth - C. Stein).

| **Property** | | **Symbol** | **Approximate value** |
|---|---|---|---|
| Geothermal flow | | q | 0 - 125 mW/m$^2$ |
| Vertical temperature gradient | | dT/dz | 10 to 80 ºC/km |
| Thermal conductivity | marine sediments | $\lambda$ | 0.6 - 1.2 W/mK |
| | continental sediments | | 1 - 5 W/mK |
| Heat generation | | S | 0-8 10$^{-6}$ W/m$^3$ |
| Specific heat | | Cp | 0.85-1.25 kJ/kg ºC |
| Density of crustal and lithospheric rocks | | $\rho$ | 2200 to 3400 kg/m$^3$ |

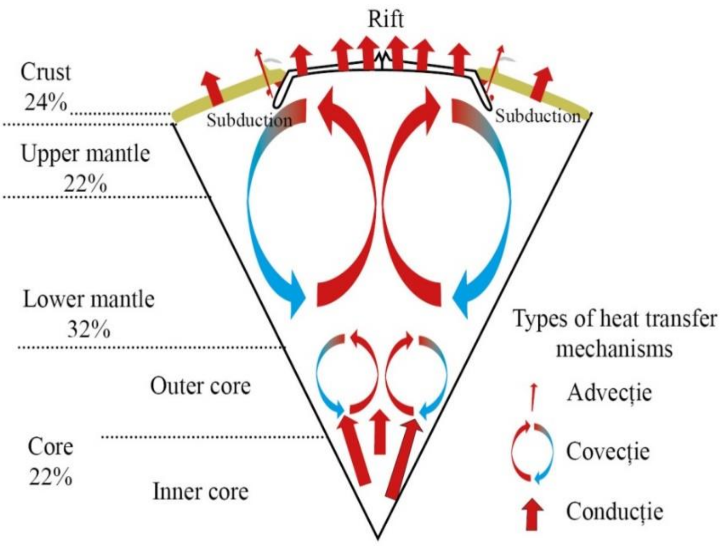


Figure 3. Heat flow transfer mechanisms and approximative percent of heat flow (after DYE, 2012).

**Geothermal gradient - $G_t$ -** measures temperature variation with depth:

$$\mathbf{G_t = \frac{\partial t}{\partial z}} \qquad \mathbf{10.}$$

Taking into account the above relationship and that of the geothermal flow it follows:

$$\boldsymbol{q = -\,\lambda \cdot G_t} \qquad \mathbf{11.}$$

The minus sign indicates that the direction of transmission is from the inside of the planet to the outside – Fig. 3).

It was calculated that $G_{t\ medium}$ = 3.3/100 m or $G_{t\ medium}$ =1/33 m

There are exceptions; areas where for various geological reasons Gt < 3.3°C/100 m such as a basin filled with "very young" sediments as a result of the bedrock having undergone rapid collapse, as well exists areas with Gt > 3.3°C/100 m such as near the crust or in areas with volcanic activity.

**Geothermal step** - the distance that must be descended, deep underground, to produce a successive increase in temperature with 1°C. It is measured in meters. It can be determined either by direct recording on site, in the laboratory or by mathematical calculation.

**Temperature** - Basically, temperature is the key parameter influencing all the above-mentioned parameters.

As can be seen from the Fig. 4 the temperature inside geological formations is influenced by the outside temperature only up to 10 m depth. After this limit it depends only on the type of rock, the type of heat transfer, the physical-chemical processes taking place in the area (proximity to areas with volcanic potential, existence of radioactive rocks, etc.).

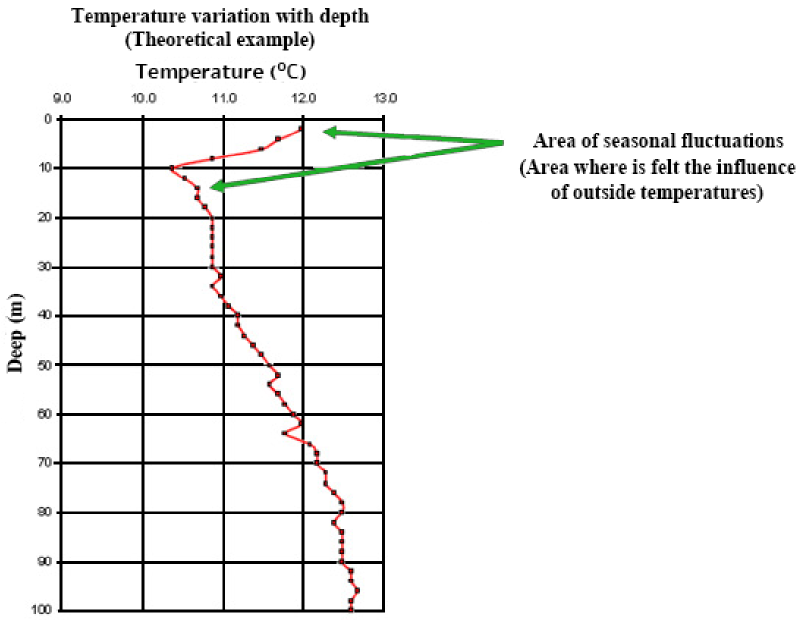


Figure 4. Variation of the temperature with deep.

## BEHAVIOR SIMULATIONS WITH DEDICATED SOFTWARE

There are several software packages that simulate the behaviour of the GSC over time, specifically the temperature evolution over time. To better understand simulations in this area it is essential to understand the principles on which it works.

The geology of different areas is complex and even at small distances between two identical targets there can be a major change in lithology resulting in a change in the amount of energy that geological formations can supply to ground-water and/or ground-air heat pump air conditioning systems. As a result, a simulation of soil behaviour for different situations is required. The Earth Energy Designer (EED) software is one of the most widely used. This software is used both to simulate soil behaviour in the heating regime and to record the thermal response of geological formations for the heating regime.

The heat field in the area around the borehole can be determined from the linear, infinite, constant intensity heat source model:

$$\Delta T(r_p,\tau) = T_p - T_s = \frac{q_E}{4\pi\lambda}\int_{\frac{x^2}{4\rho\lambda}}^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta = \frac{q_E}{4\pi\lambda}\cdot E\left(\frac{r^2}{4a\tau}\right) \quad 12.$$

where

$$a = \frac{\lambda}{\rho c} \quad 13.$$

$r_p$ - borehole radius [m]

$\tau$ - test duration **[s]**

$\Delta T(r_p,\tau)$ - temperature difference in the adjacent borehole in function of its radius and time of action

$T_p$- average borehole wall temperature [K]

$T_s$- average undisturbed soil temperature [K]

$q_E$- specific extraction or injection power [W/m]

$\lambda$ - average thermal conductivity of rock [W/mK]

$r$ - current radius [m]

$a$ - average thermal diffusivity of rocks [m2/s]

$r$ - average thermal density of rocks [Kg/m3]

$c$ - average specific heat of rocks [J/Kg K]

$\tau$ - time [s]

The equation used to determine the temperature variation between the fluid in the installation and the rocks in the area adjacent to the borehole is:

$$\Delta T(r_p, \tau) = q_e \cdot (R_p + R_s) = \frac{q_E}{4\pi\lambda} \int_{\frac{x^2}{4\rho\lambda}}^{\infty} \frac{e^{-\beta^2}}{\beta} d\beta = \frac{q_E}{4\pi\lambda} \cdot E\left(\frac{r^2}{4a\tau}\right) \qquad \textbf{14.}$$

Where:

R - Average thermal resistance of the rocks around the borehole [m K/W]

g - Euler's constant (0.5772)

An efficient heat exchange requires that the thermal resistance of the rocks around the borehole is as low as possible, thus increasing their thermal conductivity, which is almost impossible in nature. The increase in conductivity can only be achieved by the addition of moisture and this can generally only happen at shallow depths through infiltration from various sources or through tectonic movements of various magnitudes leading to stratigraphic and structural changes, etc. Technically, however, it is possible to influence the heat transfer by filling the space between the return and return of the energy capture system with a bentonite cement that ensures the lowest possible heat exchange between the two pipes. It is also essential to ensure that they are in contact with the ground over as large an area as possible, which can be achieved by using spacers, especially geo-clips type (NEGUȚ, 2009; SÂRBU & SEBARCHIEVICI, 2010).

## SIMULATION OF THE CHARACTERISTICS AND BEHAVIOR OF GEOLOGICAL FORMATIONS

The study concerned 2 types of heat exchanger respectively one with a single turn and return (Valul lui Traian and Hotel Vila 23, Snagov) and one with 2 turns and 2 return objectives (Murighiol laboratories) – details in Table 2.

All these ground heat exchangers studied are with closed vertical boreholes mounted in parallel. The same type of pipe was used for all of them with the same characteristics:

U pipe diameter- 32.00 mm

U pipe wall thickness - 3.00 mm

Thermal conductivity of U pipe - 0.420 W/(m-K)

The energy transport fluid in geological formations, in all cases, is water.

Table 2. Input data for the facilities studied.

| Project | No. Boreholes | Load [MW] | |
|---|---|---|---|
| | | Heating | Cooling |
| Showroom Vitan, București | 112 | 402.00000 | 393.000 |
| Showroom Valul lui Traian, Constanța | 357 | 1250.00000 | 1750.000 |
| Hotel Vila 23, Snagov | 128 | 0.44800 | 0.650 |
| Laboratoare Murighiol | 9 | 0.08374 | 0.073 |

Load peaks are needed to estimate the maximum possible temperature variations. Heat extraction or heat injection according to the peak load is added to the base load at the end of each month. Fluid temperatures are calculated as the minimum and maximum temperatures that can occur for peak load.

The program automatically calculates some very important parameters such as the Seasonal Performance Factor (SPF). For calculation reasons the peak load energy is assumed to be negligible because it does not influence the long-term behaviour.

## SIMULATION OF GEOTHERMAL AGENT TEMPERATURE EVOLUTION

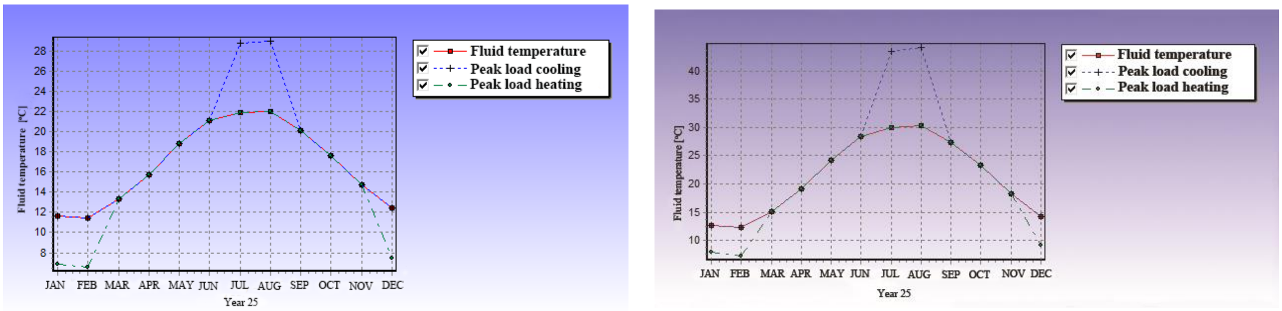


Figure 5. Fluid temperature evolution, a. - Vitan project, Bucharest, b. - Hotel Vila 23, Snagov.

Simulations concerning the evolution of the thermal agent temperatures in the installation are among the most interesting. It should not be forgotten that the temperature of the thermal agent is practically the same as that of the geological formations in the contact zone with the installation.

The EED software use algorithms that have been derived from modelling and parameter studies with a numerical simulation model (SBM) resulting in analytical solutions of the heat flow with several combinations for the bore hole pattern and geometry (g-functions) – see Fig. 5.

The evolution of the temperatures of the thermal agent has been simulated over a period of 25 years of continuous operation of the plant and in particular for the 25th year of operation.

From the analysis of the graphs given by the software, it can be seen how the average temperatures of the energy transport fluid in the geological formations (water) evolve for the thermal power for cooling, heating and domestic hot water preparation respectively for year 25 of the system operation (JAVED & CLAESSON, 2011).

Interestingly, the curves are similar in appearance and differ only in the value of temperatures in both cases. The aspect of chart guarantee that the plant will work at least without thermal problems in the ground.

## CONCLUSIONS

Studies over periods of 7-8 years show that the estimated temperature is higher than the actual temperature because the influence of energy extraction from the soil is lower than estimated. It turns out that the ability of geological formations to achieve thermal balance is higher than simulated, and this proves once again that a very good knowledge of the geological formations traversed by the thermal energy harvesting system is necessary.

However, this comparison, which has been validated by the [records], will allow the simulations to be accepted as being eloquent for other types of heat exchangers, i.e. parallel 2-circuit and coaxial as more efficient alternatives for large buildings, which have also been analysed in this research.

The temperature of the carrier fluid is an important parameter that in the case of a drop below a certain value during the operation of a geothermal heat pump system:

- leads to additional costs;
- The CoP of the pumps may fall below the level of a classic installation.

The high thermal conductivity of geological formations requires very good thermal exchange, but if the extraction is not well calibrated this can cause freeze-thaw cycles at the boundary of pipes – rocks – which leads to deterioration of the mechanical properties of the rocks in which they are quartered, a process all the more undesirable as the geo-exchanger is located either close to the served building or even below it. (PRICĂ, 2015; TSEMEKIDI-TZEIRANAKI, 2018; MARTINOPOULOS et al., 2018)

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