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# Probabilistic approach to TRT analysis: evaluation of groundwater flow effects and machine - borehole interaction

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## ABSTRACT

Thermal Response Test (TRT) measures the temperature response of a Borehole Heat Exchanger (BHE) to heat injection or extraction. The temperature response is related to the ground and borehole thermal parameters such as thermal conductivity and heat capacity; TRT is therefore used to obtain estimates on the equivalent values of these parameters. After all, the test results can be affected by different elements such as: ground temperature variations, groundwater movement (GW), weather conditions, seasonal event, etc. This work aims to analyse the relationships among the TRT results and the variability of these factors, and in particular it tries to study the effect of groundwater flow on thermal parameters. This paper aims to provide a new framework to seek possible solutions, integrating classical methodologies with probabilistic and multivariate geostatistical modelling. The instruments are the variogram and cross covariance, which are sensitive and informative with regard to the effects of groundwater flow on the TRT results. Also, the behaviour of the TRT machine with different operating and boundary conditions is captured with the geostatistical approach, yielding a good understanding of the heat exchange.

## 1. INTRODUCTION

In recent years, it has been noticed an increasing market of the so called ground coupled heat pump systems (GCHP). By installing appropriate geo-exchangers, the underground is used as a seasonal storage of thermal energy, from which it is possible to extract heat in winter and cold over the summer

In the design of GCHP systems, accurate information on the ground thermal parameters, such as thermal conductivity, heat capacity and temperature, is essential for the design of economically sized and well-functioning underground thermal energy storage (UTES). The exchange of energy between the heat exchanger and the ground and in the ground itself ground is governed by:

- Conduction term: the flow of heat by conduction between the collector pipe and the surrounding ground. Conduction is the result of temperature differences in a material and depends on the thermal conductivity of the material. In the case of a borehole heat exchanger, the thermal contact between the pipes and the surrounding ground is established by the filling material. Different natural ground components and saturation lead to different heat exchange rates.

- Advection term: the transport of heat due to movement of mass (as a result of pressure gradients, concentration gradients or temperature gradients) with different temperatures, for instance ground water. The underground is not a static system, because of the presence of different fluids (groundwater, gas), stable or in motion. Due to the dynamic behaviour of the system, the advection term is not negligible.

- Radiation term: the shallow meters of the BTES are affected by sun radiation (heat inflow) and long wave radiation losses at night.

- Convection term: the heat carrier fluid flows inside the collector in a turbulent or laminar way which affects the exchange of heat between the fluid and the pipe wall.

- Heat losses in the down- and up flowing pipes of the heat exchanger due to short-circuiting.

It is quite difficult to estimate separately these terms and the ground volume of interest during the heat transfer is related to the initial and boundary conditions. The classic methodologies for identifying the ground thermal parameters consider only the conduction term. Also today parameters are considered constant in time and space whereas in fact they should be considered as varying in time and space and a probabilistic approach is needed (Bruno et al. 2011). This paper present new methodologies and techniques, and suggest appropriate instruments which are more sensitive and informative respect to analytical method with regard to the effects of the advection and convection terms.

## 2. ANALYSIS METHOD

### 2.1 Traditional approach

The analytical solution is derived from Kelvin's line-source equation (Ingersoll and Plass, 1948; Mogensen, 1983) that describes the mean temperature increment ΔT at a radial distance r from an infinite linear source of heat having a constant heat flow rate. The steady state is considered reached when the heat flow has passed through the borehole wall. The simplified version of the Infinite Line Source (ILS) equation is expressed in a line form in the dimension of the time logarithm (Gehlin and Eklof, 1996):

$$T_f\ (t) = b \cdot \ln(t) + a \qquad [1]$$

Where:

$$a = Tg + \frac{P}{H} \cdot \left[\frac{1}{4 \cdot \pi \cdot \lambda_g} \left(\frac{\ln(4 \cdot \alpha_g)}{r_b^{\,2}}\right.\right. \qquad [2]$$

$$b = \frac{P}{4 \cdot \pi \cdot \lambda_g \cdot H} \qquad [3]$$

The model is valid in stationary conditions, and is theoretically accurate within <10% if the following inequality is respected:

$$t > 5\,\frac{r_b^{\,2}}{\alpha_b} \qquad [4]$$

The slope *b* and the intercept *a* are estimated by operating a classical linear regression on the vector of the experimental fluid data registered at different times. The parameters in the equations are:

$T_f$ (t) = fluid temperature at different times [°C],

t = time [s],

$T_g$ = average ground temperature along the borehole length [°C],

P = average power rate [W],

H= borehole lenght [m],

$\lambda_g$= equivalent ground thermal conductivity [W/(mK)],

$\alpha_g$ = equivalent ground thermal diffusivity ($\lambda_g/c_g$) [$m^2$/s],

$c_g$ = ground volumetric heat capacity [J / $m^3$K],

$r_b$= borehole radius [m],

γ= Euler's number 0,5772,

$R_b$= borehole thermal resistance [K/W/m],

$\alpha_b$ = borehole thermal diffusivity [$m^2$/s].

### 2.2 Geostatistical approach

By looking at the equation [1] is clear that there is a classical problem of parameter estimation, because the true value of *b* and *a* can be only estimated ($b^*$,$a^*$). Moreover, the temperature recorded by the experimental apparatus is influenced by several factors that cannot be controlled. Indeed when repeating a TRT, the $T_f$ profile does not exactly match the previous profiles, if a test is repeated many times and conditions are constant, the different test results will show a certain spread around an average value. This should be constant, in principle, if the theoretical hypotheses and boundary conditions strictly apply. However, the realisation of even a single test can in practice yield a simple single estimate of the parameters of interest that is one of possible values. This is due to the fact that petro-physical parameters and technical-operational parameters of TRT are not constant in the space and time. Indeed the ground volume is never completely homogenous and the temperature gradient propagates radially through the ground volume during the test. Depending on the real geology, the changes in average ground properties in the radially increasing tested zone can be minor or rather large. Moreover also fluxes, power used is not perfectly constant and also weather conditions are always slightly variable. Therefore a geostatistical approach looks like well suited to study this variability.

The proposed geostatistical approach is applied to monodimensional variables, defined in the time domain. It considers the temperature as a random function non-stationary in time (NStRF) (Chiles and Delfiner, 1999), modelled as the sum of a mean function (the expected value), m(t), deterministic, and a stationary random function (StRF), Y(t), called fluctuation or residual, with zero mean.

$$T(t) = m(t) + Y(t) \qquad [5]$$

$$E[T(t)] = m(t) = a + b \ln t \qquad [6]$$

The variables power P and the flow $Q_f$ are considered StRF. The overall random nature of the test results is transferred to fluctuations.

The main instruments used are the direct variogram of fluctuations of a single variable [7] and cross covariance of the fluctuations of a pair of different variables [8]:

$$\gamma(h) = \frac{1}{2} E\left[\left(Y(t+h) - Y(t)\right)^2\right] \qquad [7]$$

$$C_{12}\ (h) = E[Y_1(t), Y_2(t+h)] \qquad [8]$$

h is the time lag.

## 3. THERMAL RESPONSE TEST EXPERIMENT

### 3.1 Experimental apparatus

The first TRT apparatus, full electrical machines, were created at the end of nineties (Austin, 1998; Gehlin et al., 1998). The experimental apparatus of the Groenholland Geo Energy systems described by Witte et al. (2002) does not use electrical power to directly heat the circulation fluid but uses an air to water heat pump to and a control system to maintain a fixed temperature difference between the inlet and outlet. Due to this approach, the energy rate is not influenced by variations in the power supply during the experiment, as the source (the heat pump) and the borehole are decoupled. Also, whereas the electrical resistance systems can only inject heat into the ground, this system can either inject heat or extract heat. It gives more information in the layered subsurface, because the effective usable thermal conductivity may then depend on heat injection or extraction (Signorelli et al. 2004). Additional components of the system include a 0.5 $m^3$ buffer tank, two circulation pumps (one that circulates fluid between the heat pump and the buffer tank and one that circulates fluid between the buffer tank and the ground loop), a three-way regulating valve that regulates the energy flow to the ground loop, a flow sensor, and several temperature sensors. Temperature is measured in the buffer tank, in the fluid entering the ground loop, and in the fluid returning from the ground loop. The system is configured as shown in Figure 1. The heat pump generates a supply of warm or cold water. Using the temperature sensor in the buffer tank and the entering ground-loop temperature, a specified difference is maintained. This supply of energy is used to achieve a certain temperature difference between the entering and return ground-loop temperature (e.g., 2.5ºC). This temperature difference is achieved by mixing in more or less water from the buffer vessel by the regulating valve. The amount of energy injected or extracted from the ground is a function of the flow and temperature difference selected.

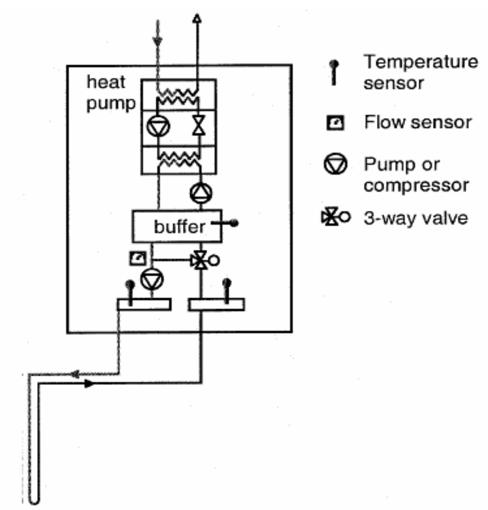


**Figure 1: Experimental apparatus**

### 3.2 In Situ Tests

Three different experiments in the same site of known stratigraphy (alternations of peaty and clayey, fine sand and coarse sand) were carried out using a 30 meter deep heat exchanger and nearby water extraction well with the filter collocated at 11-13 m deep (Figure 2). The aquifer is in principle confined and when the flow is extracted there is no change in phreatic head. The energy injected was always 1200 W, as well as energy extracted (-1200 W), so with the same temperature difference (absolute value) ΔT (°C), flow $Q_w$ ($m^3$/h) and the same circulation fluid (water 85% - monopropylene glycol 15%) and all the experiments worked for 48 hours. The main difference in the experiments is the heat mode (extraction or injection) and the presence or not of groundwater movement. The water flow extracted from the nearby well is about 0,50 $m^3$/h. From the application of the traditional approach, using the Formulas [1] and [2] on the data recorded, after 10 hours the experiments have been started, and ground thermal conductivity $\lambda_g$ and borehole thermal resistance $R_b$ were individuated; in the Table 1 the three experiments peculiarities and results are shown.

**Table 1: Summary of the main experiments characteristics and ILS results**

| N. | Heat Mode | GW flow | $\lambda_g$ W/(m K ) | $R_b$ (K/(W/m)) |
|---|---|---|---|---|
| a | Extraction | No | 1.98 – 2.40 | 0.10 - 0.16 |
| b | Extraction | Yes | 2.60 – 3.15 | 0.13 - 0.19 |
| c | Injection | Yes | 1.82 – 2.06 | 0.11 - 0.17 |

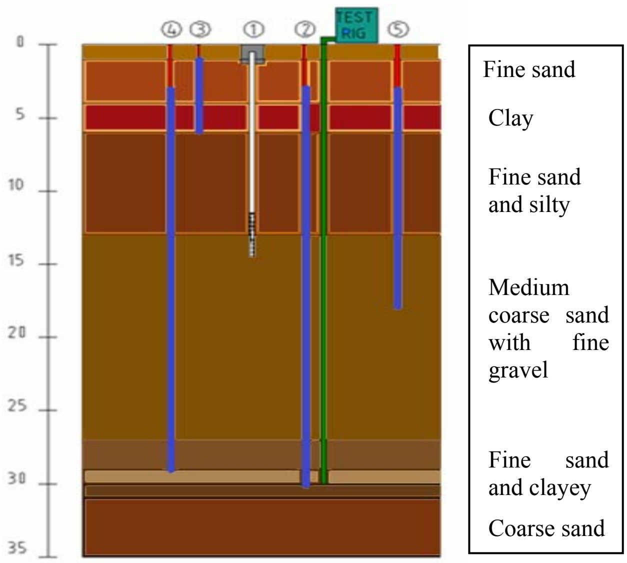


**Figure 2: Underground profile, BHE (green), water well (1) and observation points (2,3,4,5)**

The difference between the experiments is the variation of the initial conditions (initial temperature of the ground, weather conditions, etc.) and boundary conditions (groundwater flow). It is expected that the groundwater flow movement highly influence the results; other influences come from other effects as: initial temperature of the ground, weather conditions, different behaviour of the machine TRT during the experiments, etc. In the present work we tried to have a better comprehension of these effects by using a probabilistic approach.

## 4. RESULTS

### 4.1 Evaluation of influence of groundwater flow on TRT results, by traditional method

The stability and speed of convergence of the estimated ground thermal conductivity, as a function of starting time selected and of amount of data points included, is usually evaluated by using a graphical method based on the CUmulative SUM (CUSUM) test (Brown et al., 1975; Witte, 2007). These graphs are constructed by calculating estimates of ground thermal conductivity with the data points added in a stepwise fashion, each step adding a certain amount (e.g. 2 h) of data. The sensitivity to the starting time selected can be evaluated by constructing several of these series, each with a different starting time.

The GW flow usually significantly affects results of the TRT; this was expected also in the CUSUM graphs, which should show an increasing estimate with time. The reason for this is that the effect of GW depends on the difference between the ground water temperature and circulating fluid temperature. The GW flow, coupled with the temperature difference, makes the fluid temperature stabilize on a certain level during the TRT working. This should cause an increases of ground thermal conductivity results in time increment, respect to the normal value calculated by linear regression. CUSUM test should show that in presence of groundwater flow, the thermal conductivity results never reach a convergence on a unique value.

In our two experiments with GW flow this effect is not in evidence, and the conductivity results reach a convergence, no matter the initial starting time. Depending on starting time, the results are different, but anyway they converge.

In effect, the forced groundwater velocity created by artificial pressure drop, was of low magnitude and therefore the CUSUM, normally thought to be a good indicator of GW flow, is not sufficiently sensitive, as it is shown in Figure 3 (extraction) and Figure 4 (injection).

### 4.2 Evaluation of influence of groundwater flow on TRT results, by geostatistical approach

The data analysis of the three experiments has produced quite different results. Some questions arise as which experiment produces more confident results and how to control and measure this confidence.

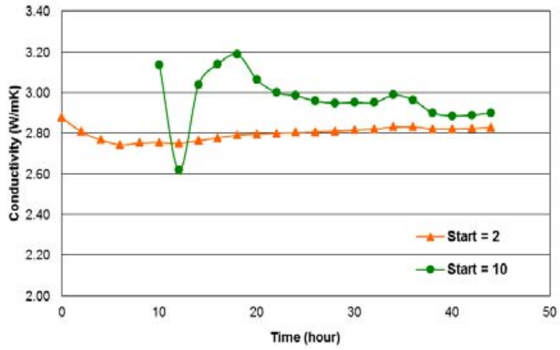


**Figure 3: CUSUM Test for experiment (b) [heat extraction with groundwater flow] Forward linear regression with different initial time**

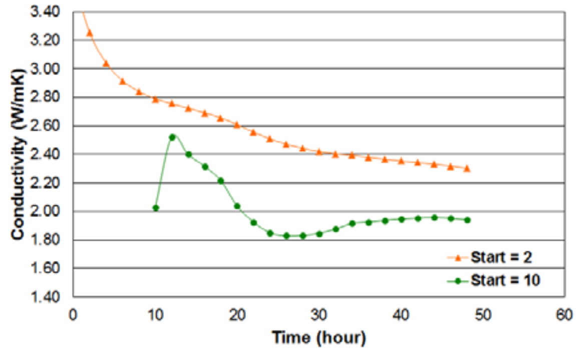


**Figure 4: CUSUM Test for experiment (c) [heat injection with groundwater flow] Forward linear regression with different initial time**

Given the wide range of causes of variation, it becomes important to understand the correlation between the experiment parameters and the results obtained by applying specific computing approaches. TRT variable inlet temperature $T_i$ (°C), outlet temperature $T_{out}$ (°C), flow Q ($m^3$/h) and power P (W) have been analysed and we adopted the geostatistical approach to study their correlation by using the temporal autocorrelation functions [7] and [8] with an elementary step of 60 s.

Comparison of the variograms for the mean temperature $T_f$ for the experiments with heat extraction with GW flow (b) and the experiment with heat injection with GW flow (c) is shown in Figure 5. The two variograms have different structures; the experiment (b) has a periodic structure due to the heat pump working, indeed in extraction mode the heat pump is switched on and off more frequent than in injection mode caused by the attention to not reach the freezing point. The experiment (c) has a structure with a smaller period due to three way-valves operating. Another important aspect of this comparison is the lower experimental variance of the experiment (c) than (b). It is possible to say that injection experiment, being less variable, is therefore more accurate than extraction experiment.

Comparison of the variograms for the mean temperature $T_f$ for the experiments in extraction heat mode without groundwater flow (a) and the experiment in heat extraction mode with groundwater flow movement (b) is shown in Figure 6. The two variograms have quite similar experimental variances, but the experiment (a) has two periodic structures: one is caused by the heat pump working, as for the experiment (b), the other is caused by the three way-valve operating. It is possible to see the effect of the groundwater flow movement on TRT: it is quite clear that the effect of the groundwater flow dampens the small scale periodic structure in the experiment (b) and forces the heat pump to produce more energy, indeed the second periodic structure is wider.

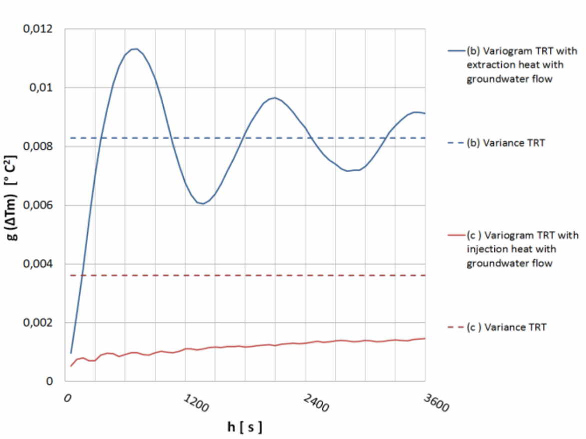


**Figure 5: Comparison of variogram of the fluctuation of average fluid temperature for the experiment (b) [heat extraction with groundwater flow] and experiment (c) [heat injection with groundwater flow]**

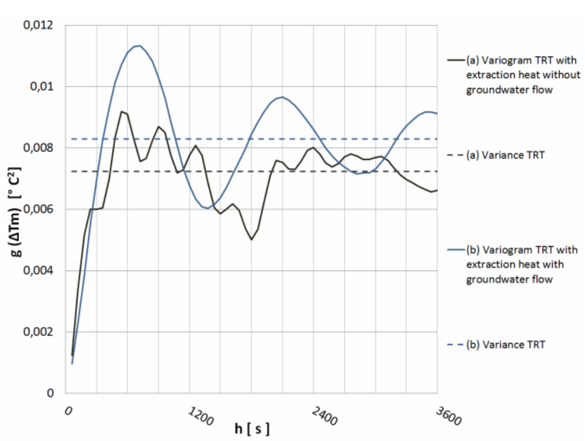


**Figure 6: Comparison of variograms of the fluctuation of average fluid temperature of the fluid for the experiment (a) [heat extraction without groundwater flow] and experiment (b) [heat extraction with groundwater flow]**

### 4.3 Other useful information about TRT, obtained by geostatistical approach

The comparison of the variograms for the inlet and outlet temperature of the fluid, during the BHE experiments, confirms that the oscillation is damped by the ground. In Figure 7 the variogram of the fluctuation of inlet temperature and outlet temperature for the experiment (a) [heat extraction without groundwater flow] is shown. It is highlighted how the structures are almost identical but with different sill and amplitude of periodic structure.

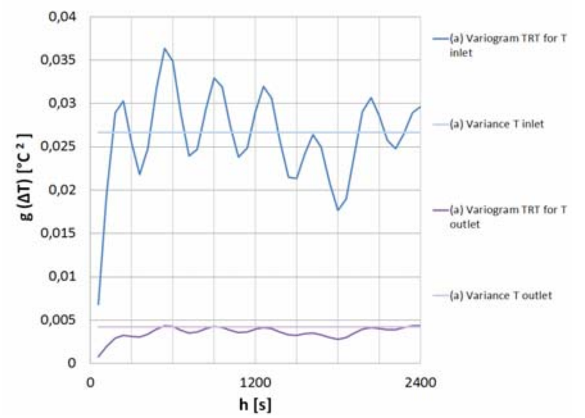


**Figure 7: Comparison of variograms of the fluctuation of inlet temperature and outlet temperature for the experiment (a) [heat extraction without groundwater flow]**

As the TRT machine works, the flow is independent from the fluid temperature. In Figure 8 the variogram of the fluctuation of the flux variable for the experiment (a) [heat extraction without groundwater flow] shows the independence of the variability over time. Indeed, the typical structure is a nugget structure without any periodic behaviour.

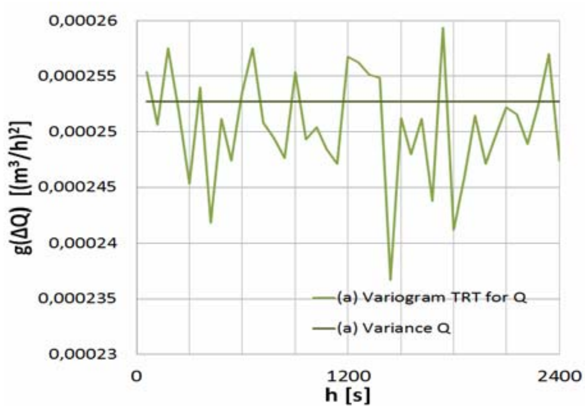


**Figure 8: Variograms of the flow fluctuation for the experiment (a) [heat extraction without groundwater flow]**

In Figure 9 the variogram of the fluctuation of power is shown. The power is function of difference between inlet and outlet temperature and of the flow, indeed the power fluctuation is a combination of the inlet and outlet fluid temperature fluctuation and of the flow fluctuation. Again it is clear the periodic nature of the time variability of power.

Through the cross-covariances is possible to determine the correlation between two different variables over time. In Figure 10 the cross covariance of the fluctuation of inlet temperature and outlet temperature is shown, which highlights that the correlation maximum is obtained not between the couple of values at the same time (lag h=0), but between values distant about 3-4 minutes. This is the delay due to the time needed by the fluid to circulate inside the BHE.

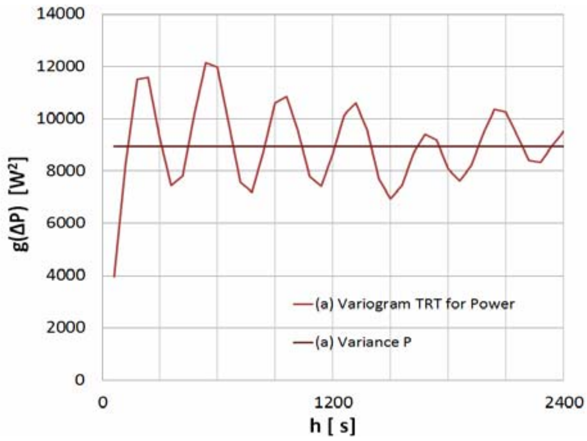


**Figure 9: Variograms of the power fluctuation for the experiment (a) [heat extraction without groundwater flow]**

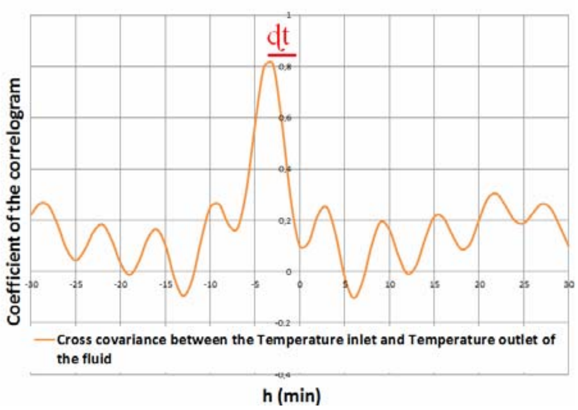


**Figure 10: Cross covariance of the fluctuation of inlet temperature and outlet temperature for the experiment (a) [heat extraction without groundwater flow]**

## 5. CONCLUSIONS

The three experiments applied the theory of Infinite Line Source; the results obtained are quite different, depending on the experiment mode (extraction, injection, GW flow, etc...). Variety and nature of the causes which generated these results cannot be studied only from a deterministic point of view, so that the work revealed the interest in concentrating the analysis on fluctuations, which characterize TRT by geostatistical instruments, typically experimental variograms and cross-covariances.

The variograms on fluctuations permit to easily visualize and understand the type of interaction between the TRT – machine and the reservoir. In particular, they show and quantify the frequency and amplitude of fluctuations both at small and large scale. The small scale frequency is linked to the interaction between the circulation fluid and the three-way valve operation. The large scale frequency is linked to the heat pump operation, in particular in extraction mode.

By the comparison between experiments (a) [heat extraction without GW flow] and (b), [heat extraction with GW flow], it has been possible to study the effect of water movement on the TRT results. Firstly, the increase of equivalent ground thermal conductivity, due to the advection term caused by groundwater movement, has been experimentally confirmed. Secondly, it has been showed by the analysis on variograms that the GW flow damps the small scale frequency, while it widens the large scale frequency, due to the increase of energy requested to heat pump to maintain the same delta of temperature of experiment (a).

By the comparison between experiments (b) [heat extraction with GW flow] and (c) [heat injection with GW flow], it has been possible to evaluate the accuracy of two heating modes; the nested structures of variograms in two cases are quite different: the solution (b) has a bigger sill than (c) and is mostly made up by cyclic structures. The difference of sill shows that the injection mode (c) is more precise than extraction mode (b); moreover, the cyclicality of structures in extraction mode shows a kind of complexity of TRT machine working, not present in injection mode.

By applying fluctuation analysis on different parameters of the same TRT (inlet temperature, outlet temperature, flow, power), it is possible to gain information about their correlation in the machine process. The analysis showed that the flow is independent by temperature over time, while power is dependent by flow and temperature over time. Finally, the cross-covariance between inlet and outlet fluid temperature easily verifies and measures the needed time for the fluid to circulate inside the BHE.

The geostatistical analysis made therefore possible to study in detail the sensitivity of TRT results to different boundary conditions, both those connected to the reservoir (ground temperature and GW flow), both those related to the machine equipment (valves, pumps and heat mode).It needs to be noted that the oscillatory behaviour due to the operation of the three way valve is in this case present due to the short length of the heat exchanger. This introduces a coupling between the flow rate and residence time of the fluid in the heat exchanger, the control parameters of the three way valve and heat pump set points. In a more typical heat exchanger length (> 50 meters) these effects are much reduced or absent. Therefore, it is a topic for further research of how to introduce oscillations in deeper boreholes, and what the optimal oscillation strategy would be.

In conclusion, integrating the traditional deterministic methods (ILS or other) with the geostatistical approach, it is possible to have a great understanding of the results obtained by TRT: such information is valuable for the design phase of the single BHE, but also of the entire geothermal field.

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