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Modification of Method of Interpreting Thermal Response Test of Borehole Heat Exchanger

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ABSTRACT

Prior to complex designing borehole heat exchangers thermal reaction tests are recommended. Proper interpretation of the obtained results reveals the actual values of effective thermal conductivity factor of the drilled profile and thermal resistance of the heat exchanger, typical of the rock mass-borehole system. A theoretical model of heat exchange in a heat exchanger has been analyzed in the paper. On an example of selected industrial tests the results of the so far interpretation TRT were compared with those obtained by a novel method, accounting for the results of heat balance in the rock mass-borehole relation. The presented analysis was aimed at optimizing the thermal reaction tests of borehole heat exchangers in view of minimization of time of the tests and so their cost.

1. INTRODUCTION

World's energy demand increases and gives initiative to search for and manage various energy sources, as the conventional ones are limited and their prices undergo considerable changes. Hence, techniques and technologies oriented to recovery of Earth's heat have been intensely developed for over 20 years. One of such energy sources are geothermal waters which, depending on their physicochemical parameters, can be used for a number of purposes, e.g. thermal pools (Pająk 2008), space heating (Dickson and Fanelli, ed. 2003) and finally electrical energy generation (Pinka et al., 2007).

Another, equally significant direction of Earth's energy recuperation is horizontal or vertical low-temperature borehole heat exchangers. This paper is devoted to the initial stage of vertical borehole heat exchangers, which usually cooperate with heat pumps (Śliwa and Gonet 2003).

2. BOREHOLE HEAT EXCHANGERS (BHE)

Generally, a borehole heat exchanger consists of a borehole with a U-pipe disposed in it. The U-pipe is filled with a fluid in a closed circulation (Fig. 1). However, a number of unknowns are involved when it comes to design details. Such parameters as BHE localization and work parameters have to be so selected as to provide optimum use of BHE in heat/cold energy production over a longer span of time, e.g. a year.

One of the first unknowns is a detailed recognition of geologic and hydrogeologic conditions of the area where BHE are planned. Among such parameters are: type of rock mass, depth of deposition and humidity. Another issue is the BHE design: either single U-pipe, two U-pipe or coaxial pipe systems. (Fig. 1). Depending on the rock mass conditions and depth of the borehole, a casing string is introduced or not. After drilling a borehole and disposing of the BHE system, the free space should be filled with material having best heat transfer qualities. Intense works are continued in World's laboratories on working out durable cement slurry, which would meet most of the technological BHE requirements, and which would have very high heat transfer factor. Other very important parameters are: materials from which BHE is made and fluid transmitting the heat to BHE (or reversely, depending on whether we want to recover heat or to accumulate it in the rock mass).

The type of BHE design influences the cost of the heat exchanger. The design also has influence on the heat exchange process. The best heat exchange parameters can be obtained for the coaxial design as it provides the largest heat exchange surface. This solution, however, is most expensive. In practice the coaxial designs are used for BHE at over 150 m of depth.

The inner diameter of borehole influences the time and cost of drilling. When the BHE is sealed with slurry of increased heat conductivity, larger diameters are more advantageous. In the thermal conductivity of rocks is higher than that of the sealing slurry, smaller diameters are advisable.

On one hand the distance between the exchanger pipes should be biggest, but this would disadvantageously lead to reducing the BHE diameter at the assumed borehole diameter.

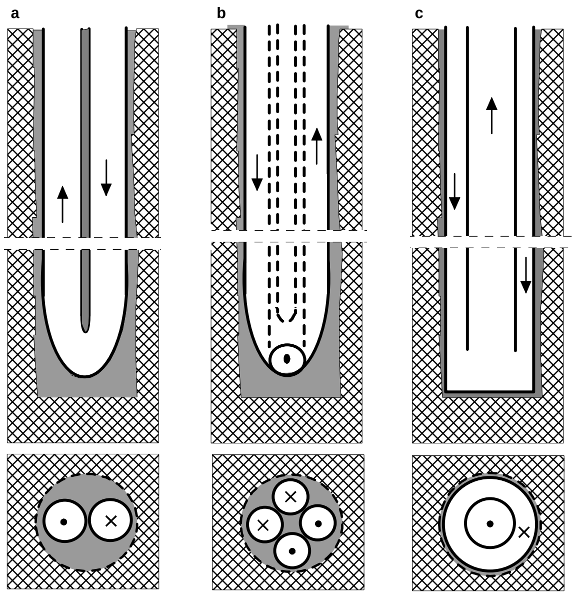

Figure 1: BHE designs,with a single u-pipe (a) or two u-pipes (b) and a coaxial system (c).

Sealing the BHE pipes should provide such borehole tightness that no flow between aquifers takes place. As far as energy is concerned, high thermal conductivity slurries are a better solution.

The diameter of BHE inner pipes, their thickness and material are also important technical and economic aspects of the analyzed BHE designs.

2. THERMAL RESPONSE TEST (TRT)

Thermal response tests (TRT) are recommended prior to designing BHE as a heat source or storage place. As a result, the geologic setting and water conditions should be well recognized. TRT is performed with a specialist device (Fig. 2). Constant fluid injection rate and constant heating power should be maintained over the test. The increased temperature of the fluid results in a growth of temperature of fluid circulating in the BHE system, which should be accurately measured at the inlet and outlet.

Figure 2: Device of thermal response tests.

Fourier law applies to the heat exchange in a BHE, where in a general case the heat flow vector $\overline{\Phi}$ in a solid material is proportionate to thermal conductivity λ and the gradient of the temperature field $\Delta\overline{T}$ e.g.

$$\overline{\Phi} = -\lambda \Delta \overline{T} \tag{1}$$

Thermal conductivity of rock mass and borehole thermal resistance cannot be measured directly, but should contain TRT data. To minimize the influence of atmospheric factors (wind, air temperature), the shortest connections between the exchanger and TRT apparatus should be used. Moreover, the connecting pipes should be thermally insulated.

The temperature field *T* as a function of *t* time and *r* radius with heating power *q* was described in literature, e.g. Eklöf & Gehlin (1996) and Austin (1998) who presented a line source model. Gehlin (2002) described a formula for a change of temperature *T* vs. distance *r* and time *t* for line source heating power:

$$T(r,t) = T_0 + \frac{q}{4\cdot\pi\cdot\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du \cong T_0 + \frac{q}{4\cdot\pi\cdot\lambda}\left[\ln\left(\frac{4\alpha\cdot t}{r^2}\right)-\gamma\right] \tag{2}$$

for $t \geq \frac{5\cdot r^2}{\alpha}$

where

T_o – mean temperature of profile, K,

q – the specific heat transfer rate, W/m:

$$q = \frac{Q}{H} \tag{3}$$

Q – the total heat rate transferred by the borehole of active length H, W,

α – thermal diffusivity, $m^2 \cdot s^{-1}$,

$$\alpha = \frac{\lambda}{\rho\cdot c} \tag{4}$$

where:

ρ - density of rocks, kg/m^3,

c – specific mass heat of rocks, J/(kg·K),

r – radius of borehole, m,

γ - Euler constant, γ = 0.5772.

The errors of the approximation in equation (2) are less than 10% for $t \geq \frac{5\cdot r^2}{\alpha}$ and less than 2,5% for $t \geq \frac{20\cdot r^2}{\alpha}$.

Thermal conductivity is the most important factor when designing a BHE system. BHE also strongly depends on the thermal resistance (R_b) between the heat carrier fluid and the borehole wall. The thermal resistance depends on the construction of the borehole, materials used and their thermal properties. R_b can be calculated from the formula:

$$R_b = \frac{1}{q}(T_f - T_0) - \frac{1}{4\cdot\pi\cdot\lambda}\left[\ln(t) + \ln\left(\frac{4\alpha}{r_o^{\,2}}\right) - \gamma\right] \tag{5}$$

where:

T_f – the mean of the inlet and outlet fluid temperatures of the heat exchanger, K,

$$T_f = \frac{T_{in} + T_{out}}{2} \tag{6}$$

T_{in} – supply temperature, K,

T_{out} – return temperature, K.

The mean temperature (T_o) can be determined on the basis of undisturbed temperature profiling (Fig. 3) or temperature parameters during heat circulation prior to TRT (Fig. 4). The T_o value, determined from undisturbed temperature profiling, equals to 12.25°C. Temperature determined on the basis of heat carrier circulation prior to TRT heating phase equals to 13.6°C. The arithmetic mean is 12.925°C.

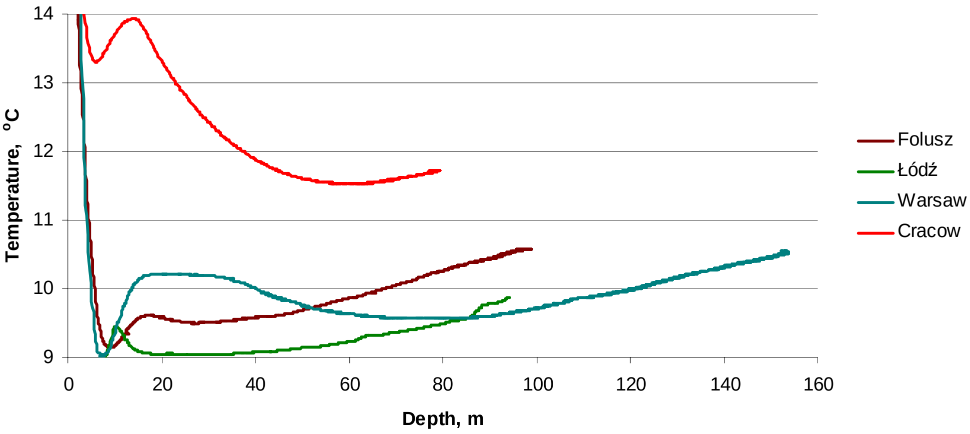

Figure 3: Undisturbed temperature (thermal equilibrium conditions) in BHE in selected places in Poland.

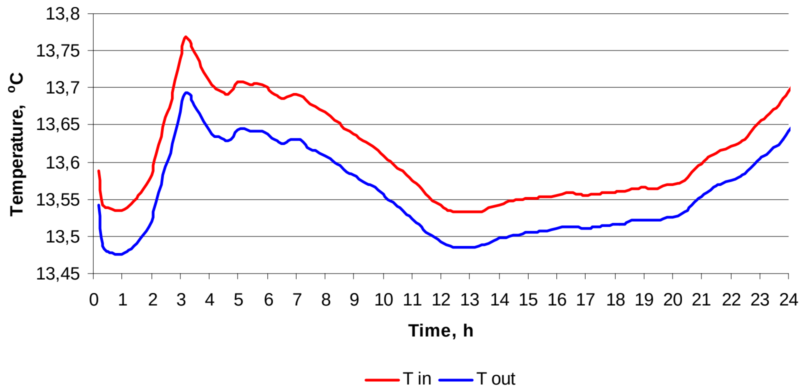

Figure 4: Temperature of heat carrier at the inlet and outlet of TRT during circulation without heating prior to TRT.

Both temperatures and time are registered during TRT. The remaining parameters are constant. As a result two curves are obtained, the examples of which are given in Fig. 5. In both curves the temperature usually rapidly changes at the initial stage to become more stable later in time. This dependence is better visible in the plot of temperature vs. logarithm of test time. Fig. 6 illustrates the change of directional coefficient of both parts of the straight line. When interpreting TRT it is crucial to determine the so-called critical time, i.e. time higher than a point of curve folt. The recommendations concerning the accuracy of interpretation and time of test realization vary, e.g. Sanner et al. (2005) say that the time should be ≥ 48-50 hrs. Skouby and Spitler et al. assume 50 hrs as minimum time of testing (Skouby 1998; Spitler et al., 1999). The physical analysis of TRT reveals that this problem is more complex, and thus depends on a number of factors. Accordingly, more parameters should be analyzed if the critical time is to be determined accurately. Hence, it is suggested that each TRT is treated individually, the plots of temperature vs. time are simultaneously drawn (Fig. 5) and on this basis TRT time and critical time are determined. Additionally, for establishing effective thermal conductivity (λ_{eff}) mathematical statistics methods are recommended. It should lie in determining a straight line with the least squares method, introducing inlet and outlet TRT temperatures. In this way twice as many measurements are introduced to the statistical analysis for the same time of the test. More accurate equation of a straight line is obtained at the same time of TRT as when determining two regression equations and mean temperature. Another feasible practical solution lies in shortening the TRT time for the assumed number of measurements. This leads to the reduction of the TRT cost. An example of such a TRT interpretation is presented in Figs. 7 and 8, where the area of confidence was additionally marked, for confidence coefficient equal to ca. 0.95. To show the influence of the above changes, TRT were performed and interpreted for various values of time, from which slope of a straight line was determined. Then the effective heat conductivity was calculated from the formula:

$$\lambda_{eff} = \frac{q}{4 \cdot \pi \cdot k} \tag{7}$$

where k is slope of a straight line in a semi logarithmic system. Exmplary BHE data are listed in Table 1:

- depth of BHE (H) 78 m,

- diameter of borehole (D_o) 143 mm,

- average density of rocks (ρ) 2500 kg/m^3,

- mass specific heat of rocks (c) 923.6 J/(kgK) – after density and volumetric specific heat are accounted for (c_V).

- volumetric specific heat (c_V) 2.309 MJ/(m^{3}K),

- diameter of U-pipes (d_z) 32 mm.

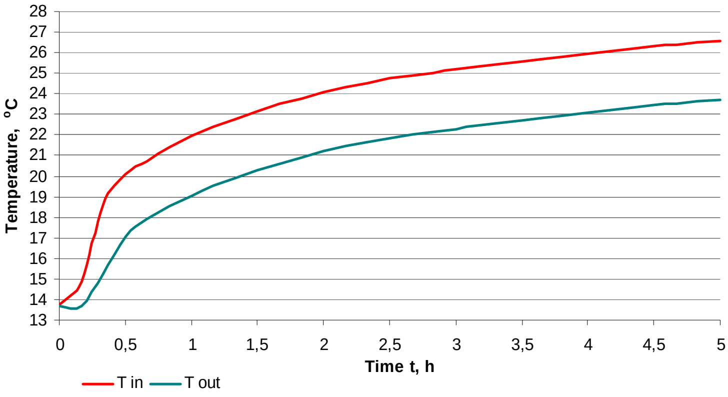

Figure 5: Dependence of supply and return temperature of heat carrier in BHE on time of the test.

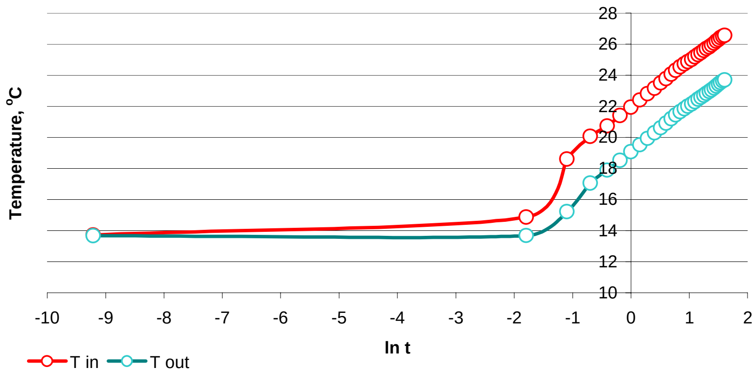

Figure 6: Dependence of supply and return temperature of heat carrier in BHE on logarithm of time of the test.

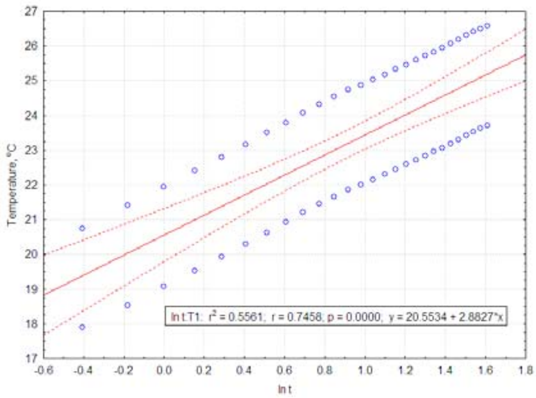

Figure 7: Regression function based on supply and return temperature after 5-hour test at confidence coefficient equal to 0.95.

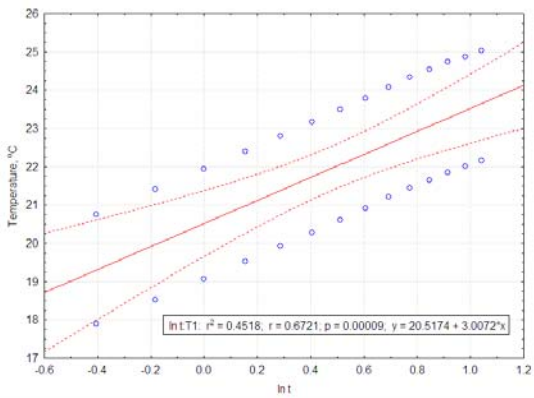

Figure 8: Regression function based on supply and return temperature after 2.5-hour TRT at confidence coefficient equal to 0.95.

The critical time was assumed to be 5, 20 and 50 hrs, and the total time of TRT heating phase of 96 hrs from the beginning of the test, as well as the times from $\frac{5 \cdot r^2}{\alpha} = 8.04\,h$ and $\frac{20 \cdot r^2}{\alpha} = 32.16\,h$ to the end of the test. The given results reveal that with the increase of time all test temperatures and effective thermal conductivity grow (table 2).

Table 1. Lithological data and thermal parameters of rocks of a selected BHE

Lithology	**Top**	**Bottom**	**Thickness of bed, m**	**Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$**	**Volumetric specific heat, $MJ \cdot m^{-3} \cdot K^{-1}$**
Clayey ground	1.8	2.2	0.4	1.5	2
Aggredate mud	2.2	2.6	0.4	1.5	2.2
Fine and dusty sand	2.6	4.0	1.4	2	2
Fine sand	4.0	6.0	2	2.2	2.5
All-in aggregate and gravel	6.0	15.0	9	1.8	2.4
Grey siltstone	15.0	30.0	15	2	2.3
Grey chale clay	30.0	78.0	48	2.1	2.3
Weighted average				**λ=2.039**	**c_v=2.309**

The value of thermal diffusivity on the basis of literature data was determined in the following way:

$$\alpha_1 = \frac{2.039\, W \cdot m^{-1} K^{-1}}{2.309 \cdot 10^6 J \cdot m^{-3} K^{-1}} = 0.8831 \cdot 10^{-6} m^2 s^{-1}$$

The interpretation lies in determining average temperature T_f from supply and return temperature of heat carrier. This temperature indicates a linear variability against logarithm of time. The slope of the straight line k is used for determining effective heat conductivity (Fig. 9) in compliance with relation 7. For comparison's sake, the courses of regression function were determined independently for supply and return temperatures. First 4 points were excluded from the analysis and this corresponds to ca. 40 minutes. A dependence of average temperature of heat carrier in a BHE on logarithm of test duration after rejecting initial points with the linear regression at confidence coefficient equal to 0.99 is presented in Fig 11.

To calculate heat resistances R_b of borehole it is important that the borehole parameters (depth H and diameter D_o), thermal properties of rocks (thermal conductivity coefficient λ, and also specific heat c and density of rocks ρ are known for determining thermal diffusivity from eq. (4).

Table 2. Results of calculations

Time interval	**Slope of a straight line (for T_{in} and T_{out}), k**	**Effective coefficient of thermal conductivity (calculated for all data T_{in} and T_{out}), λ_{eff}**
40 min – 2.5 h	**3.0072**	1.357042
2.5 – 5 h	**2.7332**	1.493084
40 min - 5 h	**2.8827**	1.415651
40 min – 10 h	**2.7045**	1.508928
10 – 20 h	**1.7176**	2.375929
40 min - 20 h	**2.4993**	1.632816
40 min – 25 h	**2.43**	1.679381
25 – 50 h	**1.9365**	2.107357
40 min - 50 h	**2.2863**	1.784935
40 min- 96 h	**2.0845**	1.957734
8 - 96 h	**1.8577**	2.196747
8 – 52 h	**2.0834**	1.958767
32 – 96 h	**1.5443**	2.642554
32 – 64 h	**1.9432**	2.100091

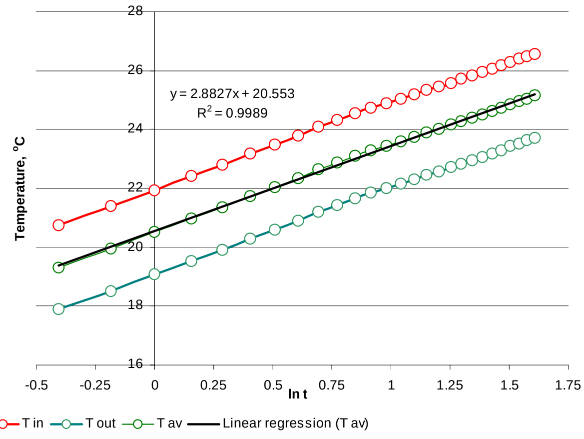

Figure 9: Dependence of supply and return temperature of heat carrier in BHE on logarithm of time after rejecting initial point with linear regression of average temperature.

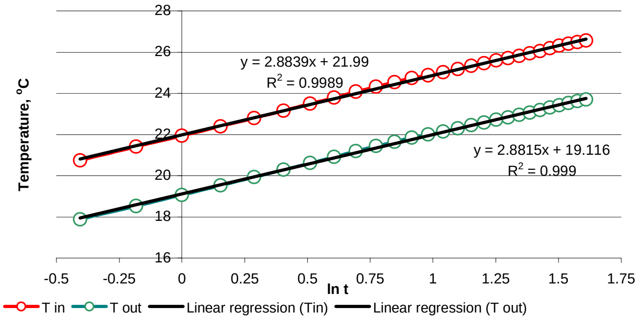

Figure 10: Dependence of supply and return temperature of heat carrier in BHE on logarithm of time of the test after rejecting initial points.

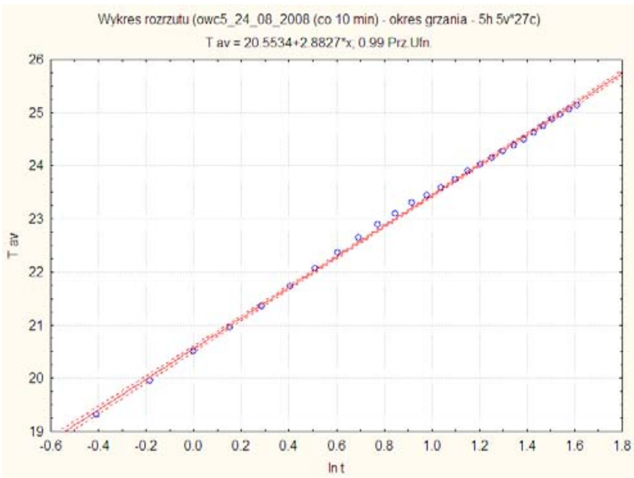

Figure 11: Dependence of average temperature of heat carrier in BHE on logarithm of time of the test after rejecting initial points (40 min) with linear regression at confidence coefficient equal to 0.99.

CONCLUSIONS

1. TRT is necessary for real recognition of thermal parameters of BHE.

2. The design of BHE considerably influences the quantity of recuperated/spent heat energy.

3. The efficiency of BHE is affected by a number of parameters, the most important of which are the design and thermal parameters of the rock mass.

4. No explicit TRT methodology or interpretation exists. The values of effective conductivity coefficient (λ_{eff}) calculated for various time intervals are presented in the paper. They were calculated for the same basic test parameters, i.e. type of heat carrier, heating power, bulk stream of heat carrier, and as a consequence various values were obtained.

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