PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

THE ANALYSIS OF EXPANSION THERMAL RESPONSE TEST (TRT) FOR BOREHOLE HEAT EXCHANGERS (BHE)

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ABSTRACT

Rational use of big borehole heat exchanger (BHE) installations necessitates performing thermal response tests (TRT) at the initial stage of works. As a result, thermal conductivity λ and borehole thermal resistance R_b are determined, i.e. parameters characterizing the rock mass and BHE construction. They are required for calculating the number of borehole heat exchangers so that heat assumptions for the entire installation can be reached. The classic TRT is usually realized with constant thermal power of 50 W/m at the heat exchanger, and time 40 to 100 hours. This solution does not provide real abilities to optimize TRT and design a complex installation of borehole heat exchangers. In this paper there was given a TRT modification, where average temperature of fluid in- and outflowing from the heat exchanger at the current analysis of regression equation used for determining the coefficient of directional coefficient of straight line k, on the basis of which thermal conductivity λ and borehole thermal resistance R_b can be calculated. It was assumed that TRT should be stopped after the time in which k does not differ more than by assumed Δk, e.g. 5%. To optimize technology of borehole heat exchangers, an extended TRT was suggested, where thermal parameters were measured at three different volume flow rate of heat carrier $\dot{V}$ and three different thermal unit powers q. To standardize the time of the extended test, 5 measurement tests were established to determine the influence of volume flow rate of heat carrier $\dot{V}$ and unit thermal powers q on thermal conductivity λ and borehole thermal resistance R_b. Numerous measurements were performed on borehole heat exchangers owned by the Geoenergetics Laboratory of Faculty of Drilling, Oil and Gas AGH University of Science and Technology to prove the theoretical and practical usability of the test.

INTRODUCTION

A considerable advancement in borehole heat exchangers based on heat pumps has been recently observed (Bjelm et al. 2010, Lund et al. 2010, Rybach and Signorelli 2010, Schellschmidt 2010). This is caused by the development of renewable energy sources, frequently financed from various funds. Among the most important advantages of this solution are simplicity of its design, operation and the fact that rock mass can be used as a source and storage of heat and cold.

For providing better technical and economic BHE exploitation parameters, one or two investigation boreholes should be performed for TRT as early as at the designing stage, especially in the case of bigger installations. This should facilitate precise determining actual values of thermal conductivity and borehole thermal resistance. Those parameters depend on a number of variables (Sliwa and Kotyza 2003). Among the most important ones are:

- lithology of drilled rocks,
- construction of borehole heat exchangers,
- physical parameters of heat carrier,
- exploitation parameters of borehole heat exchangers.

It should be emphasized that a man does not have any influence on geological conditions in a given area, though he should analyze the remaining factors and select the most advantageous solution for the planned goals.

ANALYSIS OF THERMAL RESPONSE TESTS

Prior to choosing the ultimate site of the investigation borehole for TRT, the available archival materials describing the geological and hydrogeological conditions should be analyzed. After drilling a borehole to the planned depth, pipes filled with circulation fluid should be introduced and properly sealed. The system should be equipped with two thermometers enabling one to measure the temperature of fluid in- and outflowing from the borehole, as well as in circulation pump and heater. The scheme of such a system has been presented in Fig. 1.

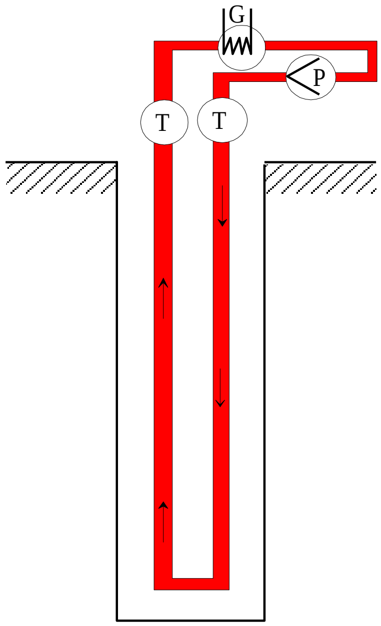

Fig. 1. Scheme of TRT of a borehole heat exchanger, T – thermometer, P – circulation pump, G – source of heat or cold – most frequently an electrical heater

The nature of TRT lies in measuring temperature changes in heat carrier (Fig. 2) as it circulates at a constant flow rate in a closed loop with heat energy of constant thermal power provided or received. It is recommended to minimize the influence of atmospheric factors on temperature in the course of such measurements (Gonet et al. 2011).

The distribution of temperature T in a function of on time t and radius of distance from the borehole axis r at a constant thermal power is described with the following equation:

$$T(r,t)=T_o+\frac{q}{4\cdot\pi\cdot\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du\cong T_o+\frac{q}{4\cdot\pi\cdot\lambda}\left[ln\left(\frac{4\alpha\cdot t}{r^2}\right)-\gamma\right] \quad (1)$$

where:

T_o – average temperature of geological profile of the borehole, K,

q – heat loses or gains per unit of depth; W·m^{-1},

$$q=\frac{Q}{H} \quad (2)$$

Q – thermal power; W,

H – depth of borehole heat exchanger; m,

λ – thermal conductivity of rocks; W·m^{-1}·K^{-1},

α – thermal diffusivity of rocks, m^2·s^{-1}, determined with the equation:

$$a=\frac{\lambda}{c_V}=\frac{\lambda}{\rho\cdot c} \quad (3)$$

c_V – volume specific heat; J·m^{-3}·K^{-1},

c – specific heat; J·kg^{-1}·K^{-1},

ρ – density of rocks; kg·m^{-3},

r – radius of borehole; m,

γ – Euler constant; γ = 0.5772156,

u – substitution; -,

$$u=\frac{r^2}{4\cdot\alpha\cdot t}. \quad (4)$$

The time of the test and time assumed as the beginning of interpretation of above function in semi-logarithmic system is important in each TRT. It was determined that according to equation (1) the calculation error is 2.5% when time is longer or equal to $20r^2/\alpha$ and 10 % when $t\geq 5r^2/\alpha$. In many TRT interpretations the temperature is determined at the inlet and outlet of heat carrier in a function of the test duration time.

Gonet and Sliwa revealed (2010) that determining the average temperature curve is more advantageous as more measuring points are available for the statistical analysis of the tests. An exemplary interpretation has been shown in Fig. 3, on the basis of which the coefficient of regression line is determined and from which effective thermal conductivity is calculated from the equation:

$$\lambda_{ef}=\frac{Q}{4\cdot\pi\cdot H\cdot k} \quad (5)$$

where:

Q – average thermal power; W,

H – depth of borehole heat exchanger; m,

k – coefficient of inclination of (straight) lines of trends, representing the plot of temperature of heat carrier vs. natural logarithm of time of TRT heating phase.

Another important BHE parameter is its thermal resistivity defined in the formula

$$R_b=\frac{1}{q}(T_{av}-T_0)-\frac{1}{4\cdot\pi\cdot\lambda}\left[\ln\frac{4\cdot\alpha\cdot t}{r_o^2}+\frac{r_0^2}{4\cdot\alpha\cdot t}-\gamma\right] \quad (6)$$

where:

q – heat losses or gain per unit of depth after eq. (2), W·m^{-1},

T_0 – average temperature of profile; ^{o}C,

λ_s – thermal conductivity of rocks; W·m^{-1}·K^{-1};

t – time; s,

α – thermal diffusivity of rocks after eq. (3); m^2·s^{-1},

r_o – radius of borehole; m,

γ – Euler constant; γ = 0.5772156.

T_{av} – average temperature of heat carrier, ^{o}C, after eq.:

$$T_{av}=\frac{T_z+T_p}{2} \quad (7)$$

T_z – feeding temperature; ^{o}C,

T_p – return temperature; ^{o}C.

The dependence of thermal conductivity for a selected BHE on time of making the test has been presented in Fig. 4.

BHE CONDUCTIVITY TEST

The TRT performed so far have made make use of constant values of flow rate of the flowing heat carrier and a constant thermal power. Those values are usually assumed arbitrarily, which does not enable one to rationally optimize work parameters of BHE. For this reason, the extended TRT, later called conductivity test, is recommended in the case of bigger installations. Its realization should follow the below scheme.

1. Design test BHE on the basis of well recognized geological and hydrogeological conditions.
2. Assume fluid which will be the heat carrier, and determine its technological parameters.
3. Assume limitations (Fig. 5) resulting from:
   a) behavior of turbulent flow $\dot{V}_{cr}$ in BHE and $\dot{V}_{acc}$ results from the technical-economic analysis (considerable pressure loses of flow and increase of exploitation cost related with circulation pump);
   b) minimal and maximal unit power expected in the analyzed BHE.
4. Perform a simplified (Fig. 5a) or full conductivity test (Fig. 5b).
5. Calculate coefficients defining the influence of unit power and flow rate of heat carrier on λ.

The selection of the number of BHE, their distribution and BHE work parameters can be optimized on the basis of the above results.

Having realized the first three tasks and analyzed the presented issue it was assumed that the thermal conductivity λ depends on the unit thermal power q and flow rate of heat carrier in an exponential function, which can be written as:

$$\lambda = c \cdot q^{a} \cdot \dot{V}^{b} \qquad (8)$$

where:

c – coefficient characterizing the system of rock mass–BHE,

a – coefficient defining influence of unit thermal power on λ,

b – coefficient defining influence of heat carrier's flow rate on λ.

Basing on complex analyses of the whole issue, one of the conductivity test variants should be selected and detailed coordinates of measuring points established. The simplified conductivity test (Fig. 5a) should be followed by the calculation of coefficients of the model (8) using the following equations:

$$a = \frac{\ln \frac{\lambda_3}{\lambda_1}}{\ln \frac{q_2}{q_1}} \qquad (9)$$

$$b = \frac{\ln \frac{\lambda_2}{\lambda_1}}{\ln \frac{\dot{V}_2}{\dot{V}_1}} \qquad (10)$$

$$c = \frac{\lambda_1}{q_1^{a} \cdot \dot{V}_1^{b}} \qquad (11)$$

For the full conductivity test (Fig. 5b) the following formulae have been employed:

$$a = \frac{\ln \frac{\lambda_4 \cdot \lambda_5}{\lambda_2 \cdot \lambda_3}}{2 \cdot \ln \frac{q_3}{q_2}} \qquad (12)$$

$$b = \frac{\ln \frac{\lambda_3 \cdot \lambda_4}{\lambda_2 \cdot \lambda_5}}{2 \cdot \ln \frac{\dot{V}_3}{\dot{V}_2}} \qquad (13)$$

$$c = \frac{\lambda_1}{q_1^{a} \cdot \dot{V}_1^{b}} \qquad (14)$$

The above conductivity tests have been realized at the Laboratory of Geoenergetics, Faculty of Drilling, Oil and Gas, AGH-UST in Cracow, Poland.

CONCLUSIONS

1. Thermal response tests extended to the conductivity test are recommended at the initial stage of designing bigger BHE installations.
2. The conductivity test lies in performing separate TRT for various values of unit heating power and flow rate of the carrier. The following operations are recommended:
   - perform a simplified test for two q and $\dot{V}$ values, which gives three measuring points (Fig. 5a),
   - make a full test for three q and $\dot{V}$ values, which corresponds to five TRT (Fig. 5b). The above test parameters should meet assumed limitations resulting from, e.g. maintaining turbulent flow of the heat carrier and unit heating power.
3. Knowing the calculated values defining the influence of unit heating power, flow rate of the carrier and a factor characterizing the BHE-rock mass system on thermal conductivity λ, one may optimize the BHE installation at the stage of designing.

Under grant of Polish Ministry of Science and Higher Education, no. N524 353738, AGH UST no. 18.18.190.505

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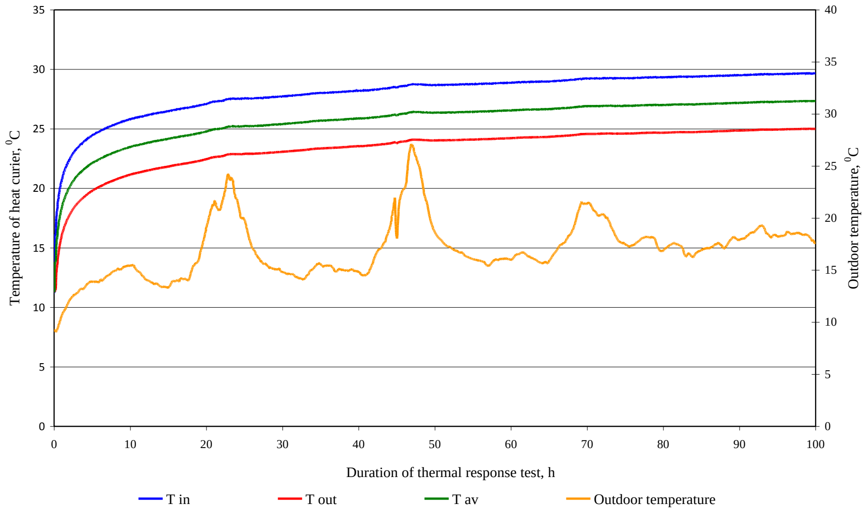

Fig. 2. Temperature of heat currier during TRT (Gonet 2011)

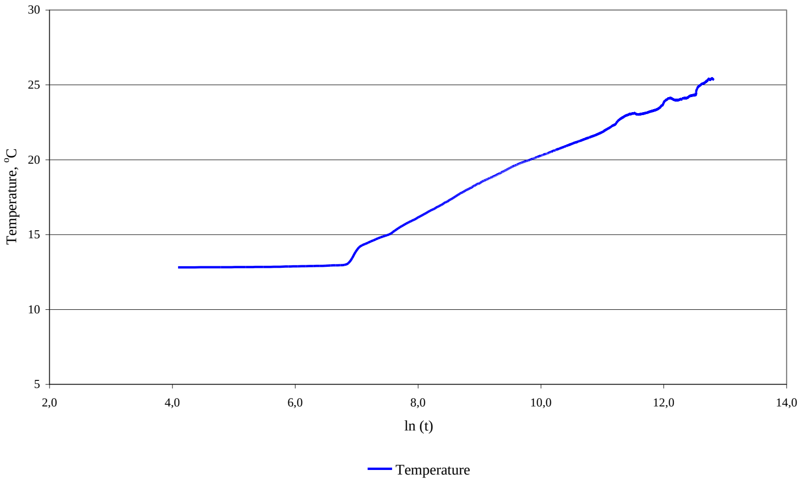

Fig. 3. Dependence of temperature of returning heat carrier vs. logarithm of time in a borehole heat exchanger in Szczecin (Gonet 2011)

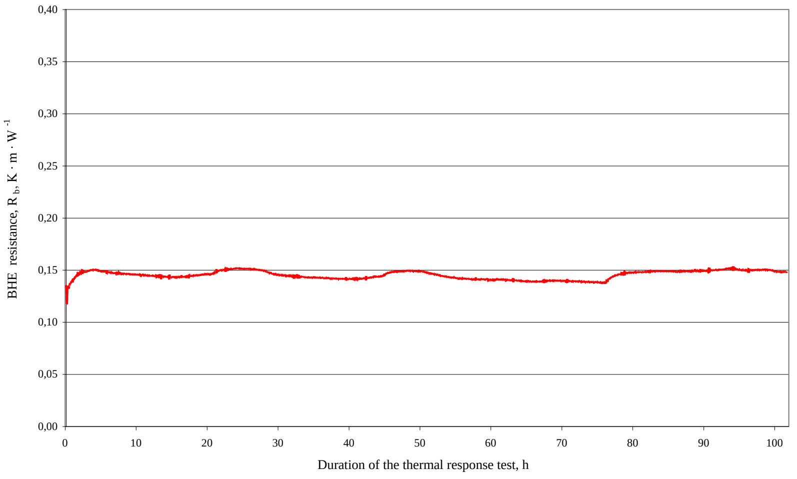

Fig. 4. Thermal conductivity over the time of TRT duration (Gonet 2011)

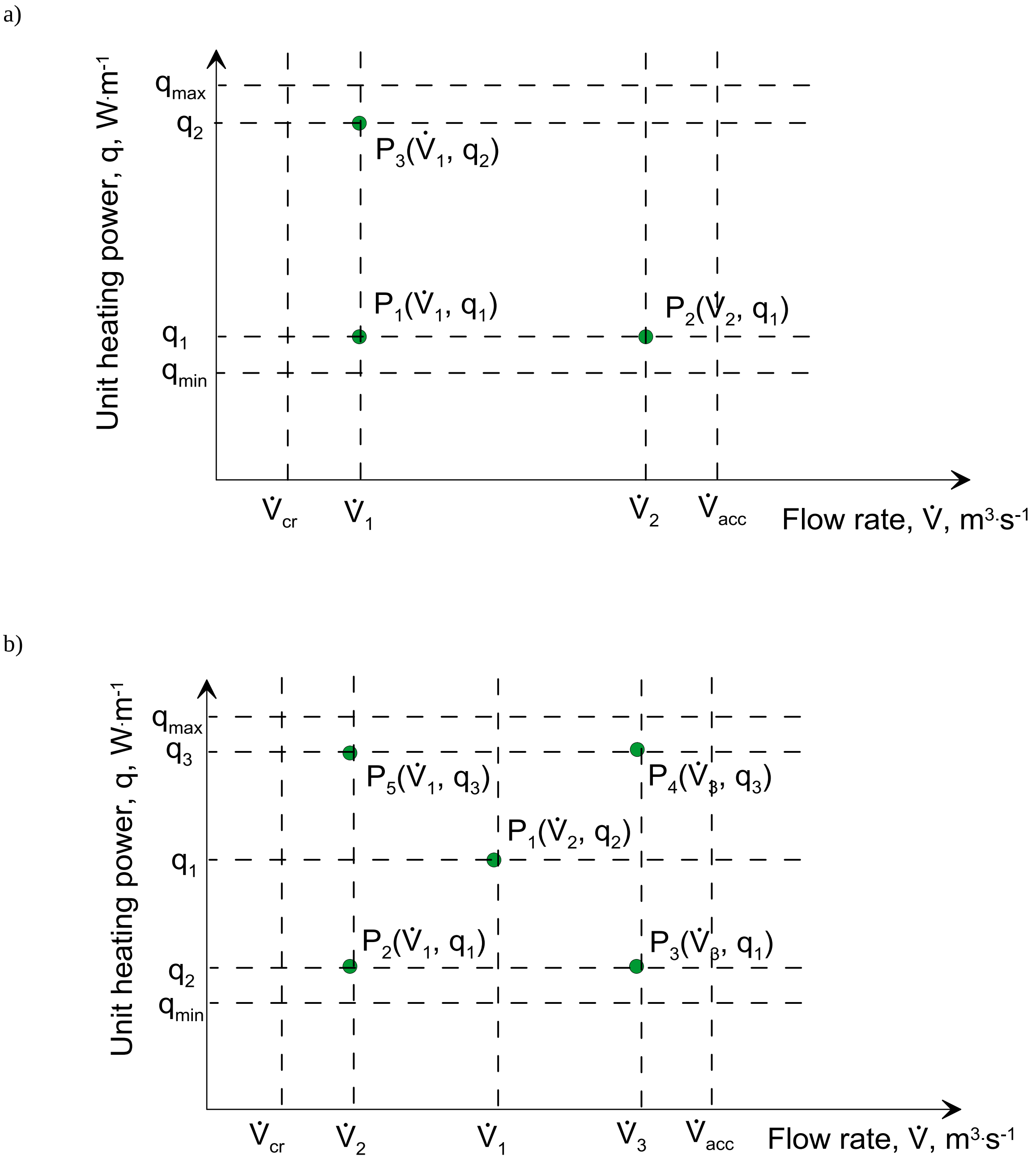

Fig. 5. Flow rate of heat carrier and unit thermal power in conductivity test a) simplified, b) full