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Thermal Response Test – Current Status and World-Wide Application

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ABSTRACT

To design borehole heat exchangers (BHE) for Ground Source Heat Pumps (GSHP) or Underground Thermal Energy Storage (UTES), the knowledge of underground thermal properties is paramount. In small plants (residential houses), these parameters usually are estimated. However, for larger plants (commercial GSHP or UTES) the thermal conductivity should be measured on site.

A useful tool to do so is a thermal response test, carried out on a BHE in a pilot borehole (later to be part of the borehole field). For a thermal response test, basically a defined heat load is put into the hole and the resulting temperature changes of the circulating fluid are measured. Since late 1990s, this technology became more and more popular, and today is used routinely in many countries for the design of larger plants with BHEs, allowing sizing of the boreholes based upon reliable underground data.

The paper includes a short description of the basic concept and the theory behind the thermal response test, looks at the history of its development, and emphasizes on the world-wide experience with this technology.

INTRODUCTION

The knowledge of underground thermal properties is a prerequisite for correct design of borehole heat exchangers (BHE). The most important parameter is the thermal conductivity of the ground. This parameter is site-specific and cannot be influenced by engineering. The thermal contact from the borehole wall to the fluid inside the pipes, however, is controlled by borehole diameter, pipe size and configuration, pipe material, and the filling inside the annulus. These items are subject to efforts in order to reduce the thermal resistance between borehole wall and fluid, usually summarised in the parameter “borehole thermal resistance”.

Since the mid 90s a method has been developed and refined to measure the underground thermal properties on site, and mobile equipment for these measurements has been built in several countries.

The Thermal Response Test (TRT, also sometimes called “Geothermal Response Test”, GRT) is a suitable method to determine the effective thermal conductivity of the underground and the borehole thermal resistance (or the thermal conductivity of the borehole filling, respectively). A temperature curve is obtained which can be evaluated by different methods. The thermal conductivity resulting is a value for the total heat transport in the underground, noted as a thermal conductivity. Other effects like convective heat transport (in permeable layers with groundwater) and further disturbances are automatically included, so it may be more correct to speak of an “effective” thermal conductivity λ_{eff}. The test equipment can be made in such a way that it can be transported to the site easily, e.g. on a light trailer (fig. 1).

Figure 1: Swedish test rig, coupled to a borehole heat exchanger

DEVELOPMENT OF THE THERMAL RESPONSE TEST

The theoretical basis for the TRT was laid over several decades (e.g. by Choudary, 1976; Mogensen, 1983; Claesson et al., 1985; Claesson and Eskilson, 1988; Hellström, 1991). In the 90s the first practical applications were made, e.g. for the investigation of borehole heat storage in Linköping (Hellström, 1977).

In 1995 a mobile test equipment was developed at Luleå Technical University to measure the ground thermal properties for BHE between some 10 m to over 100 m depth (Eklöf and Gehlin, 1996; Gehlin and Nordell, 1997). A similar development was going on independently since 1996 at Oklahoma State University in the USA (Austin, 1998). The first TRT in Germany were performed in summer 1999 (Sanner et al., 1999).

A somewhat different test rig was developed and tested in the Netherlands (van Gelder et al., 1999): This rig uses a heat pump instead of electric resistance heaters, in order to be able to also decrease the temperature inside the BHE. This method, however, has intrinsic problems because of the dynamic behaviour of the heat pump and the need for a heat source/sink, and should only be used where testing with extracting heat has to be done explicitly. Beside the Dutch test rig, at least two other have a heat pump system, on in Germany and one in Sweden.

As to the information available to the authors, there are test rigs operational today in the following countries:

- Canada
- Chile (experimental)
- China
- Germany (4)
- Netherlands
- Norway
- South Korea
- Sweden (several)
- Switzerland
- Turkey
- United Kingdom
- USA (several).

OPERATION OF THE TEST

The general layout of a TRT is shown in fig. 2. For good results, it is crucial to set up the system correctly and to minimize external influences. This is done easier with heating the ground (electric resistance heaters) than with cooling (heat pumps). However, even with resistance heating, the fluctuations of voltage in the grid may result in fluctuations of the thermal power injected into the ground.

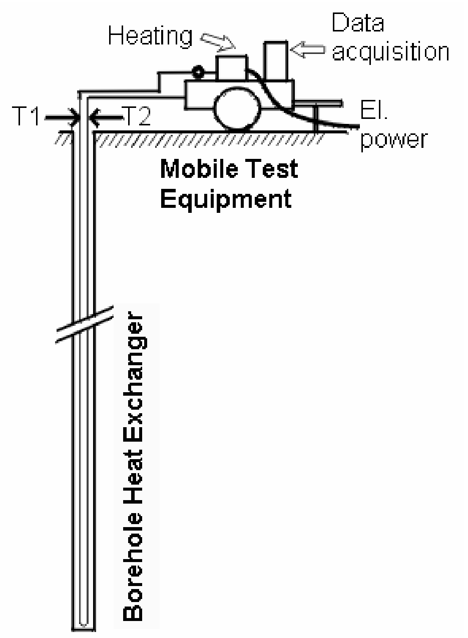
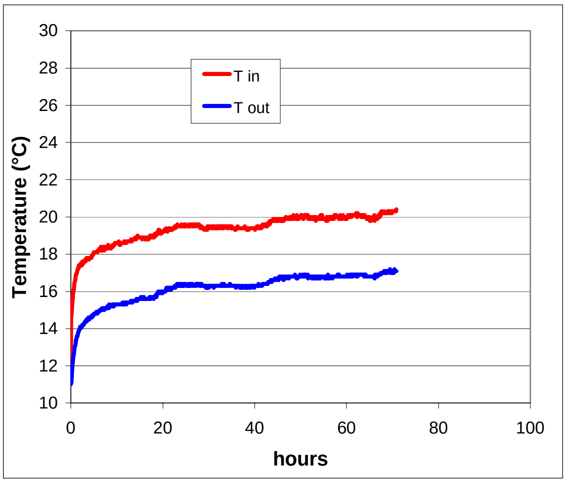


Figure 2: Test setup for a Thermal Response Test (drawing UBeG GbR, Wetzlar)

Another source of deviation are climatic influences, affecting mainly the connecting pipes between test rig and BHE, the interior temperatures of the test rig, and sometimes the upper part of the BHE in the ground. Heavy insulation is required to protect the connecting pipes (fig. 1), and sometimes even air-conditioning for the test rig is necessary, as was done in USA (fig. 3). With open or poorly grouted BHE, also rainwater intrusion may cause temperature changes. A longer test duration allows for statistical correction of power fluctuations and climatic influence, and results in more trustworthy evaluation. Typical test curves with strong and with low climatic influence are shown in fig. 4.

With the increasing commercial use of TRT, the desire for a shorter test duration became apparent, in particular n the USA. A recommendation for a minimum of 50 hours was given (Skouby, 1998; Spitler et al., 1999a), which is compatible with the IEA recommendations (see below), but there is also scepticism (Smith, 1999). A test time of ca. 12 hours is desired, which also would allow not to have the test rig out on the site over night, In general, there are physical limits for the shortening of the measuring period, because a somewhat stable heat flow has to be achieved in the ground. In the first few hours, the temperature development is mainly controlled by the borehole filling and not by the surrounding soil or rock. A time of 48 h is considered by the authors as the minimum test period.

Figure 3: OSU test apparatus on site in Nebraska



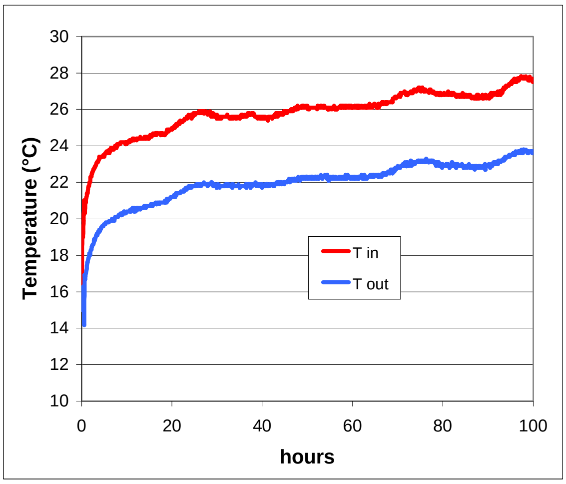


Figure 4: Measured temperature curves with low (above) and strong (below) climatic influence (data courtesy of UBeG GbR. Wetzlar)

In the evaluations made of German tests, the minimum duration criterion as noted by Eklöf and Gehlin (1996) proved helpful:

$$t_b = \frac{5r^2}{\alpha} \qquad [\ 1\ ]$$

with t_b lower time limit of data to be used
r borehole radius
α thermal diffusivity with estimated values ($\alpha = \lambda / \rho c_p$)

However, an optical cross-checking is recommended, because the measured data may deviate from the theoretical assumptions. It is also worthwhile to calculate the minimum duration criterion again with the thermal conductivity resulting from the first evaluation, to start a kind of iteration.

TEST EVALUATION

The easiest way to evaluate thermal response test data makes use of the line source theory. This theory already was used in the 40s to calculate the temperature development in the ground over time for ground source heat pump plants (Ingersoll and Plass, 1948). An approximation is possible with the following formula, given in Eklöf and Gehlin (1996):

$$k = \frac{Q}{4\pi H \lambda_{eff}} \qquad [\ 2\ ]$$

with k Inclination of the curve of temperature versus logarithmic time
Q heat injection/extraction
H length of borehole heat exchanger
λ_{eff} effective thermal conductivity (incl. influence of groundwater flow, borehole grouting, etc.)

To calculate thermal conductivity, the formula has to be transformed:

$$\lambda_{eff} = \frac{Q}{4\pi H k} \qquad [\ 3\ ]$$

A more complicated method to evaluate a thermal response test is parameter estimation using numerical modelling, as done for instance at a duct store in Linköping (Hellström, 1997). Further work on parameter estimation was done, among others, at Oklahoma State University by Spitler et al. (1999), Spitler et al. (2000), and at Oak Ridge National Laboratory (Shonder and Beck, 1999).

Spitler et al. (1999) found a deviation of ±5 % in thermal conductivity between different methods of evaluation, if data over 50 hours were used, but ±15 % when using only the first 20 hours. A comparison of four different evaluation methods is reported in Gehlin and Hellström (2003), and as a result the inclusion of data below 30 hours elapsed time into the evaluation may not be recommended. Busso et al. (2003) compared three evaluation methods with data from a 9-day-test in Chile, and conclude: “Application of the classical slope determination and/or two-variable parameter fitting can be used as a fast and reliable tool for data evaluation. Accuracy of the evaluation depends on the care taken when performing the test.”

In consequence, more advanced evaluation methods (parameter estimation through numerical simulation) can enhance accuracy and give additional information, but can reduce test time only slightly.

EXPERIENCES FROM THERMAL RESPONSE TESTING

The first test in Germany was made for a large office building in Langen (south of Frankfurt, see Seidinger et al., 2000). It was done with the equipment of UBeG GbR in summer 1999 (fig. 5).

Figure 5: Test rig of UbeG GbR on site in Langen

Figure 6 shows the regression curve of the mean fluid temperature from 6.9 to 50 hours, on a logarithmic time scale. The inclination of the curve after 7 hours is 1.411, and using formula [3] and the values given in table 1, the thermal conductivity can be calculated:

$$\lambda_{eff} = \frac{4900}{4\pi\ 99 \cdot 1.411} = 2.79 \qquad [\ 4\ ]$$

A second value that can be determined by a response test is the borehole thermal resistance. For Langen, it was calculated as r_b = 0.11 K/(W/m). This value gives the temperature drop between the natural ground and the fluid in the pipes. It is also possible to calculate r_b from the dimensions and materials used (e.g. with the program EED, Hellström et al., 1997); the result in the case for Langen is r_b = 0,115 K/(W/m) and matches nicely the measured value.

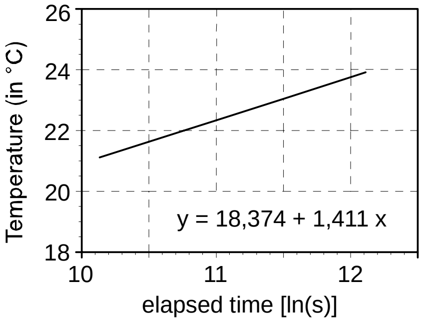


Fig. 6: Regression curve of mean fluid temperature in Thermal Response Test in Langen 1999

Table 1: Parameters of the first TRT in Germany, in Langen in 1999

test duration	50.2 h
ground temperature	12.2 °C
injected heat	4.90 kW
depth of BHE	99 m
borehole diameter	150 mm

Fig. 7: Different thermal response test rigs, from above: Early rig from Landtechnik Weihenstephan, rig built by UBeG for export to China, light rig built by hp system tech in South Korea, laboratory rig at Beijing University of Technology, China

The TRT meanwhile is used routinely for commercial design of BHE systems. The exact knowledge of ground thermal properties allows to reduce safety margins necessary when estimating the parameters, and thus the TRT becomes economic for systems comprising ca. 10 BHE and more.

LIMITATIONS OF THERMAL RESPONSE TEST

A limitation to TRT is the amount of groundwater flow. Because the thermal conductivity obtained includes convection effects, with high groundwater flow the thermal conductivity *sensu strictu* becomes masked, and the values cannot be used for design of BHE plants. The groundwater flow considered here is not the simple velocity (the time a water particle travels from one point to another, e.g. in m/s), but the Darcy-velocity, which is a measure for the amount of water flowing through a given cross-section in a certain time ($m^3/m^2/s$, resulting also in m/s). The Darcy-velocity thus depends on the porosity and the velocity.

A useful method to check for excessive groundwater flow in the standard line-source evaluation is the step-wise evaluation with a common starting point and increasing length of data-series. The resulting thermal conductivity for each time-span can be calculated and plotted over time. Usually in the first part of such a curve the thermal conductivity swings up and down, converging to a steady value and a horizontal curve in the case of a prefect test. If this curve continues to rise (i.e. the more heat is carried away the longer the test lasts), a high groundwater flow exists and the test results may be useless (fig. 8).

This method also shows if other external factors (weather, unstable power for heating, etc.) are disturbing the measurement.

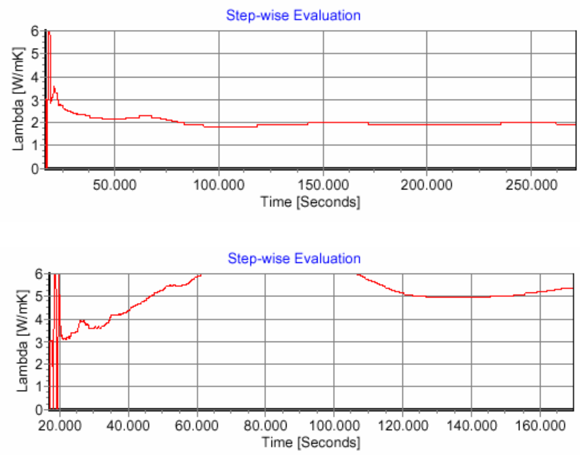


Figure 8: Step-wise evaluation showing perfect convergence (above) and test with high groundwater flow (below) and unreasonably high thermal conductivity value (data courtesy of UBeG GbR. Wetzlar)

An even more problematic kind of groundwater influence is groundwater flow upwards or downwards in the borehole annulus. This occurs in open boreholes (Sweden, see above), but also in poorly grouted BHE or in those backfilled with sand. In combination with confined aquifers or other vertical pressure differences this leads to tests which cannot be evaluated at all. Fig. 9 shows an example.

Groundwater flow so high that the test data cannot be used at all is not very frequent, at least not in Germany. Among more then 30 tests made by UBeG GbR, only 4 had strong groundwater influence, and only two did not yield any practical result (see fig. 9). However, in this case the TRT can detect a problem due to vertical groundwater movement, and authorities can become active to protect the groundwater quality.

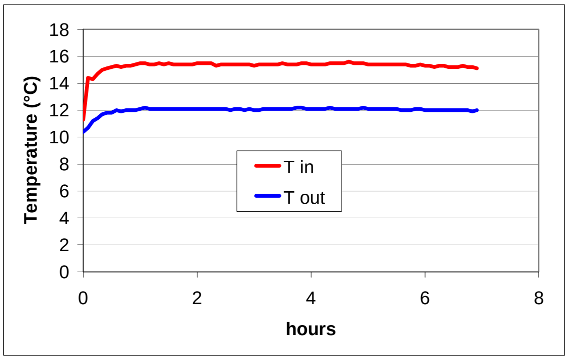


Figure 9: TRT with vertical groundwater flow along the borehole axis

RELIABILITY OF THERMAL RESPONSE TEST

Results from TRT can be reproduced, and different rigs on the same site did yield similar results. On a site in Mainz, Germany, two tests were made in virtually the same underground conditions. The results (table 2) show a very close match of the ground thermal conductivity; the borehole thermal resistance varies somewhat and is generally on the high side, which was caused by the use of an inadequate grouting material.

Table 2: Results of two test on the same site in summer 2003

	thermal conductivity	borehole thermal resistance
Mainz 1	1.43 W/m/K	0,16 K/(W/m)
Mainz 2	1,41 W/m/K	0,20 K/(W/m)

In Langen (Seidinger et al., 2000) a total of 4 tests was made in the same wellfield. One of the tests was performed with equipment from Eastern Germany in order to compare the results, but due to external acts no trustworthy data could be obtained with this test. The results of the other three tests are listed in table 3. While tests 2 and 3 show very similar results, test 1 is somewhat different. The reason is that test 1 was performed a year before the others (1999), and 2 and 3 were done during the construction of the BHE-field in 2000. The BHE for test 1 was 99 m deep, the depth was decreased to 70 m during the design optimisation (for cooling), and thermally enhanced grout was used in 2 and 3. So in test 1 different geological layers are affected, and a different grout is used.

Table 3: Results of 3 test on the Langen site

	thermal conductivity	borehole thermal resistance
Langen 1	2,8 W/m/K	0,11 K/(W/m)
Langen 2	2,3 W/m/K	0,08 K/(W/m)
Langen 3	2,2 W/m/K	0,07 K/(W/m)

A comparison of three different TRT-rigs was done in October 2000 at the site for a new Borehole storage system in Mol, Belgium. A workshop within IEA ECES Annex 12 and 13 allowed to bring one Dutch and two German rigs together. 3 BHE with different grout were available for the test. The Dutch rig had done the test before the workshop, the two German ones were doing tests on different BHE at the same time. The following BHE were available:

- Single-U, grouted with sand produced while drilling
- Single-U, grouted with specially graded sand
- Single-U, standard bentonite/cement grout

Figure 10 shows the temperature curve from UBeG as an example. Table 4 lists the results from the different rigs.

One of the tests of Groenholland had some problems during the test period and should not be considered (values in italics). The other tests resulted all in a thermal conductivity of the ground between 2,40 and 2,51 W/m/K, while the borehole thermal resistance was different according to the various backfill materials. In the saturated underground situation in Mol simple sand had the lowest thermal resistance, while the standard bentonite grout did not perform well.

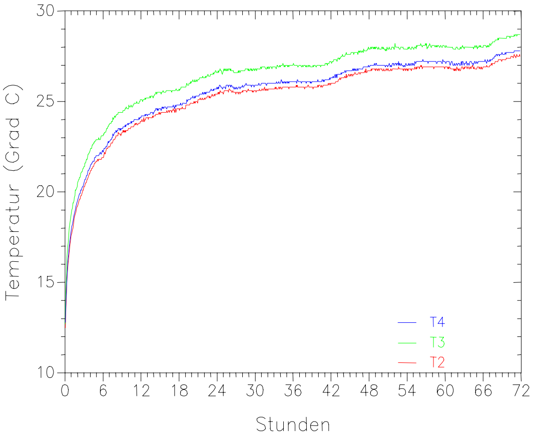


Figure 10: Temperature curve measured with the UBeG test rig in Mol, one sensor missing because of failure

Table 4: Results of the TRT comparison in Mol, Belgium, Oct. 2000

Grout	Groen-holland	UBeG	Weihen-stephan
Mol-Sand	$\lambda = 2.47$ $r_b = 0.06$	-	$\lambda = 2.47$ $r_b = 0.05$
Graded Sand	$\lambda = 2.40$ $r_b = 0.1$	-	$\lambda = 2.51$ $r_b = $ n/a
Bentonite	*$\lambda = 1.86$* *$r_b = 0.08$*	$\lambda = 2.49$ $r_b = 0.13$	-

Values for λ in W/m/K, for r_b in K/(W/m)

THERMAL RESPONSE TEST IN SUPPORT OF BHE OPTIMISATION

A parameter where engineering can help to increase the efficiency of a BHE is the borehole thermal resistance. With increasing the thermal conductivity of the borehole filling (grout), the borehole thermal resistance is decreased. Table 5 shows the theoretical improvement for some examples. The TRT now allows to check these theoretical assumptions in practice. Table 6 lists a number of TRT performed just by one company in Germany, and the tests with thermally enhanced grout are marked. In fig. 11 the borehole thermal resistance is plotted against the borehole diameter. As should be expected, borehole thermal resistance increases with increasing borehole diameter; however, to well distinct fields of data can be seen, for standard and for thermally enhanced grout. The TRT thus allows to verify the effect of the decreased borehole thermal resistance in the reality.

Table 5: Influence of thermal conductivity on the borehole thermal resistance, calculated with EED (borehole diameter 150 mm, pipe size 32 mm, shank spacing 70 mm)

Type of BHE	λ grout	r_b
single-U, PE	0.8 W/m/K	0.196 K/(W/m)
	1.6 W/m/K	0.112 K/(W/m)
double-U, PE	0.8 W/m/K	0.134 K/(W/m)
	1.6 W/m/K	0.075 K/(W/m)

Table 6: TRT results from Germany with standard grout and with thermally enhanced grout (*) (data courtesy of UBeG GbR. Wetzlar)

Borehole diameter	Thermal conductivity λ_{eff}	Borehole thermal resistance r_b
150 mm	2,8 W/m/K	0,11 K/(W/m)
194 mm	1,5 W/m/K	0,11 K/(W/m)
150 mm	2,5 W/m/K	0,12 K/(W/m)
200 mm	2,0 W/m/K	0,12 K/(W/m)
146 mm	2,7 W/m/K	0,10 K/(W/m)
160 mm	2,3 W/m/K	* 0,08 K/(W/m)
180 mm	2,3 W/m/K	* 0,08 K/(W/m)
150 mm	2,5 W/m/K	0,13 K/(W/m)
160 mm	3,1 W/m/K	0,10 K/(W/m)
200 mm	4,0 W/m/K	* 0,08 K/(W/m)
150 mm	2,2 W/m/K	* 0,07 K/(W/m)
180 mm	3,4 W/m/K	* 0,06 K/(W/m)
150 mm	2,7 W/m/K	0,10 K/(W/m)
180 mm	2,7 W/m/K	* 0,08 K/(W/m)
200 mm	1,6 W/m/K	0,11 K/(W/m)
180 mm	3,8 W/m/K	* 0,08 K/(W/m)
180 mm	3,0 W/m/K	0,16 K/(W/m)
160 mm	3,1 W/m/K	* 0,06 K/(W/m)
160 mm	3,0 W/m/K	* 0,09 K/(W/m)
130 mm	3,3 W/m/K	* 0,07 K/(W/m)
180 mm	3,8 W/m/K	* 0,08 K/(W/m)
178 mm	1,4 W/m/K	0,20 K/(W/m)
178 mm	1,4 W/m/K	0,16 K/(W/m)
130 mm	2,7 W/m/K	*0,07 K/(W/m)
150 mm	2,2 W/m/K	*0,10 K/(W/m)
120 mm	2,0 W/m/K	*0,06 K/(W/m)
120 mm	5,4 W/m/K	0,11 K/(W/m)
152 mm	1,2 W/m/K	0,21 K/(W/m)

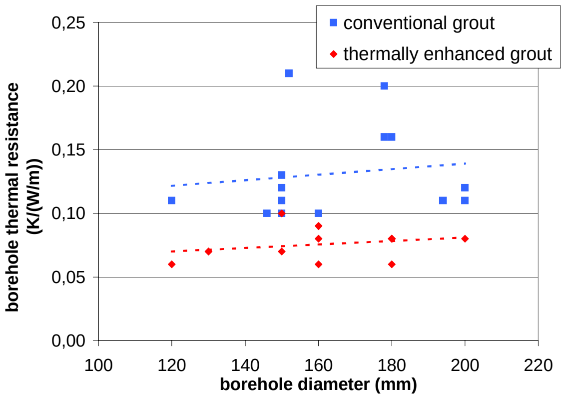


Fig. 11: Borehole thermal resistance versus borehole diameter for the data of tab. 6

DESIGN OF TEST EQUIPMENT

The question has to be discussed if measuring while heating or while cooling the ground is more suitable. One aspect is the substantially less complex construction of test equipment with electric resistance heating, having a positive impact on reliability and control. In theory, measurement with heating should yield almost the same values as measurement with cooling of the BHE, at least in underground conditions dominated by conductive heat transfer.

It is known that thermal conductivity of rocks decreases with rising temperature. This effect is not strong within the temperature changes usually occurring with GSHP (on the order of 0.05 W/m/K per 10 K temperature change); however, with high temperature thermal energy storage it may have to be considered. Hence measurements with decreasing temperature are required only at sites where thick, unsaturated sediments are expected, resulting in changing thermal conductivity due to heating-induced moisture movements. Also in cases where the real heat pump heating mode shall be investigated, e.g. including freezing of ground water, a heat pump operated TRT-rig makes sense.

The reasons for some differing effective thermal conductivity measurements with heating and with cooling at the same site still have to be elucidated. In Sweden, in BHE in open boreholes filled with groundwater, the measured data may change with the heat injection rate, due to convection in the borehole annulus (Gehlin, 1998). However, it is not yet clear if also heating-induced convection in porous aquifers can result in differing values and thus may explain the discrepancies mentioned above.

Experience with the first test has shown that a remote controlling of the test equipment is desirable. Today it is easy to establish a modem connection via mobile phone, and to download the data wherever the test equipment is located. Thus the operation can be checked regularly without a specialist going on site each time. A remote switch-off is also helpful if a temperature recovery curve shall be measured after the test itself.

CONCLUSIONS AND OUTLOOK

TRT has developed into a routine tool for investigating ground thermal parameters for the design of BHE plants (fig. 12). The concept has proven reliable and results are reproducable. A prerequisite therefore is high accuracy in the temperature sensing, diligent test setup and operation, and sufficiently long test time. The standard line-source-based evaluation method is sufficient in most cases and can be enhanced by step-wise evaluation. Parameter estimation with numerical modelling can yield additional accuracy and information it required.

TRT is done in Europe, North America and East Asia, and a first test was reported from South America. Of course the need for test is there where BHE are to be installed.

Further development of TRT points in two directions:

- "Quick and dirty" tests with reduced accuracy for routine checking in quality control during the construction of BHE-fields, or for design of small systems in residential houses
- More sophisticated tests with additional information, e.g. vertical thermal conductivity distribution along the BHE (Heidinger et al., 2004; Rohner et al., 2004)

Guidelines for TRT are required to prevent inadequate testing and ensure the necessary accuracy for a given task. A draft guideline has been developed by an expert group of IEA ECES Annex 13 (comprising also the authors of this paper), and was published as an appendix to Eugster and Laloui (2001). The German guideline VDI 4640 will also incorporate partly this IEA draft in the course of the ongoing revision. The IEA guideline draft is printed at the end of this paper.

Figure 12: TRT-equipment of UBeG GbR on site for design of a BHE field in Aachen, Germany

REFERENCES

Austin, W.: Development of an in-situ system for measuring ground thermal properties. MSc-thesis, OSU, 164 p., 1998

Bose, J.E., Smith, M.D. and Spitler, J.D.: Advances in Ground Source Heat Pump Systems - An International Overview. *Proc. 7th IEA Heat Pump Conf.,*. 313-324, 2002.

Busso, A., Georgiev, A., and Roth, P.: Underground thermal energy storage – first thermal response test in South America. *RIO 3 - World Climate and Energy Event*, 189-196, 2003

Choudary, A.: An approach to determine the thermal conductivity and diffusivity of a rock in situ. - PhD-thesis, OSU, 1976

Claesson, J., Eftring, B., Eskilson, P. and Hellström, G.: Markvärme, en handbok om termiska analyser. 3 vol., SCBR T16-18:1985, Stockholm 1985

Claesson, J. and Eskilson, P.: Conductive Heat Extraction to a deep Borehole, Thermal Analysis and Dimensioning Rules. *Energy* 13/6, 509-527, 1988

Cruickshanks, F., Bardsley, J. and Williams, H.: In-Situ Measurement of Thermal Properties of Cunard Formation in a borehole, Halifax, Nova Scotia. *Proc. Terrastock 2000*, 171-175, 2000

Eklöf, C. and Gehlin, S.: TED - a mobile equipment for thermal response test. MSc-thesis 1996:198E, LuTH, 62 p., 1996

Eugster, W.J., Sanner, B. and Mands, E.: Stand der Entwicklung und Anwendung des Thermal-Response-Test. – *Proc. 7. Geothermische Fachtagung*, 304-314, 2002

Eugster, W.J. and Laloui, L. (eds.): Proc. Workshop Geothermische Response Tests Lausanne, GtV, 124 p., 2001

Gehlin, S. and Nordell, B.: Thermal Response Test - a Mobile Equipment for Determining Thermal Resistance of Borehole. - *Proc. Megastock '97*, 103-108, 1997

Gehlin, S. Thermal Response Test - In-situ measurements of thermal properties in hard rock. Lic.-thesis 1998:37, LuTH, 1998

Gehlin, S. and Hellström, G.: Recent Status of In-Situ Thermal Response Tests for BTES Applications in Sweden. - *Proc. Terrastock 2000*, 159-164, 2000

Gehlin, S.: Thermal response test – Method development and evaluation. Doctoral Thesis 2002:39, LuTH, 2002

Gehlin, S. and Hellström, G.:. Comparison of four models for thermal response test evaluation. *ASHRAE transactions,* 109, 1 –12, 2003

Heidinger, G., Dornstädter, J., Fabritius, A., Welter, M., Wahl, G. and Zurek: EGRT – Enhanced Geothermal Response Test. *Proc. 8. Geothermische Fachtagung*, 316-323, 2004

Hellström, G. : Ground Heat Storage, Thermal Analysis of Duct Storage Systems, I. Theory. 262 p., LTH, 1991

Hellström, G.: Fluid-to-ground thermal resistance in duct ground heat storage. *Proc. Calorstock '94*, 373-380, 1994

Hellström, G.: Thermal response test of a heat store in clay at Linköping, Sweden. *Proc. Megastock '97*, 115-120, 1997

Ingersoll, L.R. and Plass, H.J.: Theory of the ground pipe heat source for the heat pump. *Heating, Piping and Air Conditioning* 20/7, 119-122, 1948

Mands, E. and Sanner, B.: In-situ-determination of underground thermal parameters. *Proc. IGD Germany 2001 Bad Urach,* Suppl. 45-54,.2001

Mands, E. and Sanner, B.: Erfahrungen mit kommerziell durchgeführten Thermal Response Tests in Deutschland. *Geothermische Energie* 32-33/01, 15-18, 2001

Mogensen, P.: Fluid to Duct Wall Heat Transfer in Duct System Heat Storages. *Proc. Int Conf Subs Heat Storage,* 652-657, 1983

Rohner, E., Rybach, L. and Schärli, U.: Neue Methode zur in-situ-Bestimmung der Wärmeleitfähigkeit für die

Dimensionierung von Erdwärmesonden-Feldern. *Proc. 8. Geothermische Fachtagung*, 324-328, 2004

Sanner, B., Reuss, M. and Mands, E.: Thermal Response Test - eine Methode zur In-Situ-Bestimmung wichtiger thermischer Eigenschaften bei Erdwärmesonden. *Geothermische Energie* 24-25/99, 29-33, 1999

Sanner, B., Reuss, M., Mands, E. and Müller, J.: Thermal Response Test - Experiences in Germany. *Proc. Terrastock 2000*, 177-182, 2000

Seidinger, W., Mornhinweg, H., Mands, E. and Sanner, B.: Deutsche Flugsicherung (DFS) baut Low Energy Office mit größter Erdwärmesondenanlage Deutschlands. *Geothermische Energie* 28-29/00, 23-27, 2000

Shonder, J.A. and Beck, J.V.: Determining Effective Soil Formation Thermal Properties from Field Data Using a Parameter Estimation Technique. *ASHRAE Transactions*, 105(1), 458-466, 1999

Skouby, A.: Thermal Conductivity Testing. *The Source* 11-12/98, 1998

Smith, M.: Comments on In-Situ Borehole Thermal Conductivity Testing. *The Source* 1-2/99, 1999

Spitler, J.D., Rees, S. and Yavuzturk, C.: More Comments on In-situ Borehole Thermal Conductivity Testing. *The Source* 3-4/99, 1999

Spitler, J.D., Yavuzturk, C. and Jain, N.: Refinement and Validation of In-situ Parameter Estimation Models. short report, OSU, 1999
http://www.mae.okstate.edu/Faculty/spitler/pdfs/insitu.pdf

Spitler, J.D., Yavuzturk, C. and Rees, S.J.: In Situ Measurement of Ground Thermal Properties. *Proc. Terrastock 2000*, 165-170, 2000

Van Gelder, G., Witte, H.J.L., Kalma, S., Snijders, A. and Wennekes, R.G.A: In-situ-Messung der thermischen Eigenschaften des Untergrunds durch Wärmeentzug. – *Proc. OPET-Seminar Erdgekoppelte Wärmepumpen*,. 56-58, 1999

Witte, H.J.L., van Gelder, G. and Spitler, J.D.: In-Situ Thermal Conductivity Testing: A Dutch Perspective. *ASHRAE Transactions*. 108(1), 263-272, 2002

Appendix:

GUIDELINES FOR THERMAL RESPONSE TESTING

- Draft -

The following guidelines for Thermal Response Tests have been developed by the working group of Annex 13 “wells and boreholes” of the Implementing Agreement on Energy Conservation through Energy Storage of the International Energy Agency (IEA).

DEFINITION OF THERMAL RESPONSE TEST

For a Thermal Response Test, a defined thermal load is applied to a borehole heat exchanger and the temperature development of the inlet and outlet temperature are measured over time. This temperature response allows extrapolation of the thermal behaviour in future time. The test may be done using a device that is transportable and can be brought on-site to the borehole.

One possible conceptual model for the interpretation is to assume the ground to be a conductive medium and to determine the apparent thermal conductivity and other thermal parameters of this medium.

This guideline will show the test set-up, operation and evaluation for this procedure.

Basic requirements for a Thermal Response Test are:

- Use a power load as steady as possible.
- Record the development of the inlet and outlet temperature of the borehole heat exchanger.
- Do this for a minimum time of ca. 50 hours
- Evaluate according to rules set in this guidelines

MEASUREMENT EQUIPMENT

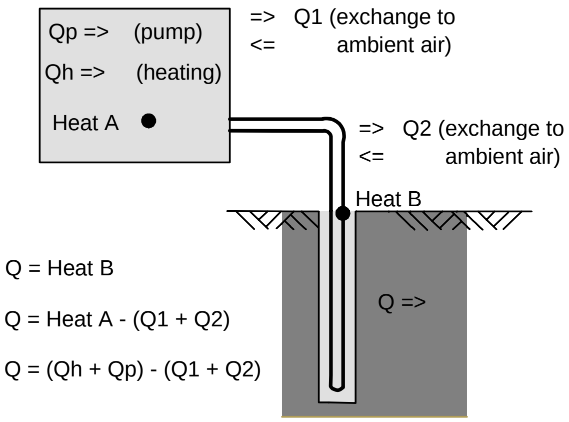
The equipment must be able to supply a steady heat load. Under certain circumstances, a cooling load may be required. This is in particular the case when freezing effects should be investigated and possibly also at ground conditions with high possible convective flow.

The heat or cold source should allow several thermal load steps. A circulation pump is required, and the flow rate should be adjustable. Suitable safety devices should be installed, e.g. against over-heating, loss of flow etc.

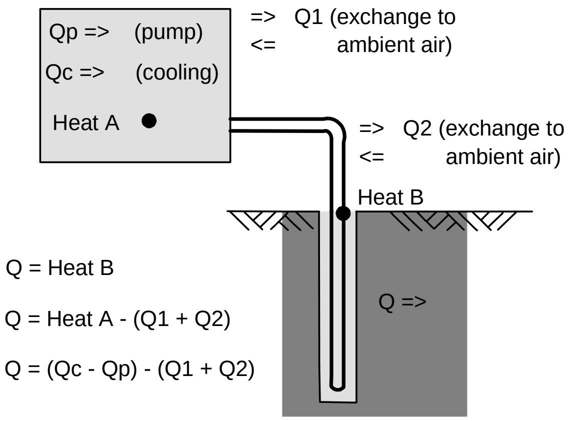
The actual injected power Q has to be determined according to the following figure. The recommended way of doing so is to measure the temperature difference in point B and the flow rate (details on required accuracy are still under discussion).

The temperature measurement should be done in point B. The time resolution of the data recordings should be maximum interval of 10 minutes. In the case of evaluation with parameter estimation method (see below) it may be necessary to record the first few hours at shorter intervals. To minimise the influence of Q1 and Q2, insulation of the equipment and piping is required in order to eliminate load fluctuations. It is recommended to also record the ambient air temperature.

It is recommended to use a remote monitoring system to keep track of the temperature development.



A) System with heat injection into the ground



B) System with heat extraction from the ground

SET UP OF TEST ON SITE

On site the system has to be connected tightly to the borehole heat exchanger and the connecting pipes should be thermally insulated. The connection between the test device and the borehole should be as short as possible. The borehole heat exchanger and the fluid circuit of the test device must be filled with heat carrier fluid, preferably water. If freezing of the fluid circuit may occur, an anti-freeze mixture of known heat capacity should be used. It is important to thoroughly remove all air trapped in the fluid circuit, and suitable air purging devices should be installed.

OPERATION

At the same time as the circulation pump is started, temperature recording should start.

To determine the initial ground temperature, to options are possible.

A) Measuring the temperature profile inside the heat exchanger pipes (without circulation) or, in case of an open, groundwater filled borehole, measuring the temperature in the annulus outside the pipes.

B) With a short time interval (e.g. 10 sec.), record the first 10-20 minutes of pumping through the pipe without heating/cooling. The data shows the temperature of the borehole profile as the plug-flow in the u-pipe passes the temperature sensors.

After this preliminary actions the heating (or cooling) load is switched on. The thermal load should be chosen in such a way that the change in fluid temperature from the starting temperature is as close at possible to that change that is expected in the operation of the final system. The expected temperature change can be calculated with an estimated thermal conductivity. Typical values for low conductivity rock are about 30 W/m and for high conductivity rock about 80 W/m. More values shall be given in a table in the final version.

The flow rate should be chosen so that turbulent flow in the borehole heat exchanger is ensured throughout the entire measurement. Values for typical flows shall be given in a table in the final version.

The test should run with a steady thermal load for at least 50 hours.

EVALUATION

For evaluation, there are two basic principles:

- The line-source approximation
- A parameter estimation using a numerical model.

These two concepts assume a purely conductive heat transfer. There may however be other modes of heat transfer in the ground such as convective heat transfer by groundwater flow. We chose therefore to use the term ”effective thermal conductivity” for the resulting value.

LINE SOURCE: To allow for the line source approximation to be applied, the temperature curve after an initial time period should show a straight line as a function of logarithmic time. This initial time period is about 10-15 hours. The apparent thermal conductivity is obtained by determining the slope k of the curve and then using the following equation, where q is the specific thermal load:

$$\lambda = \frac{q}{k \cdot 4 \cdot \pi}$$

PARAMETER ESTIMATION: Use of a numerical model, and variation of the input values for the desired parameters until theoretical values for the temperature match the measured curve. The easiest way is to use a purely conductive model (no matter how many dimensions).

These two methods are equal if the heat/cold injection rate is stable.

CONCLUDING REMARKS

Warning: check out for laminar or turbulent flow. If the test has been done with turbulent flow, but the system later is laid out for laminar flow, a correction has to be made. In general, it is desirable to avoid a varying Rb during the test. Rb is dependent on viscosity etc, so one should be careful when choosing flowrate, temperature range etc, if the Rb-estimation from the test shall be used for design of the operational system.

The evaluated parameters should be used with design methods based on the same conceptual model as the evaluation procedure.

- Draft of guideline -