Thermal Response Test for BTES Applications - State of the Art 2001

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ABSTRACT

The thermal conductivity of the ground and thermal resistance of the borehole heat exchanger (BHE) are important design parameters for BTES systems and may be determined from in situ measurements, giving reliable design data. Such tests are usually economically feasible when designing BTES systems comprising more than a few boreholes. The measurement method has rapidly developed in the last decade and is now usually referred to as Thermal Response Test. Since the initial mobile test rigs were built in 1995 in Sweden and USA, this technology has been utilized in a number of countries. This paper refers to the state-of-the-art report resulting from work done within IEA ECES Annex 13, Subtask A2 "Thermal Response Test for UTES Applications". A summary of thermal response testing activities and the current status of the equipment, analysis methods, and test experiences of thermal response testing until December 2001 is presented.

1. INTRODUCTION

This paper is a compiled version of the state-of-the-art report resulting from work done within IEA ECES Annex 13, Subtask A2 "Thermal Response Test for UTES Applications" [1]. The international co-operation project Annex 13 covers aspects of test drilling, well and borehole design, construction and maintenance of wells and boreholes for UTES applications. Proper design of borehole heat exchangers (BHE) for commercial and institutional buildings utilizing ground source heat pump systems requires a good estimate of the thermal conductivity of the ground in order to avoid significantly over-sizing or under-sizing the ground heat exchanger. A good estimate of the thermal conductivity is also needed when designing a BTES (Borehole Thermal Energy Storage) system. The ground thermal properties may be measured in situ at a specific location using thermal response test. In a thermal response test, a constant heat injection or extraction is imposed on a test borehole. The resulting temperature response can be used to determine the ground thermal conductivity, and to test the performance of boreholes. Mogensen [2] first presented the thermal response test as a method to determine the in situ values of ground thermal conductivity and thermal resistance in BHE systems. Mogensen's method was used to evaluate existing BHE systems at several occasions. The first mobile measurement devices for thermal response testing were independently constructed in Sweden and USA in 1995.

2. MEASUREMENTS AND EQUIPMENT

Mainly eight countries (Sweden, Canada, Germany, Netherlands, Norway, Turkey, United Kingdom, and USA) have developed the technique. Recently also France and Switzerland have taken up using the method. Existing measurement devices are summarized in Appendix 1 and performed tests by country are compiled in Appendix 2.

The Swedish response test device, TED, was constructed at Luleå University of Technology in 1995-96 [3]. In late 2000, Çukurova University, Turkey, took over one of the two Swedish test rigs. The Swedish TED design has been used also in Norway [4] and Canada [5] and has been the inspiration of the three rigs that are in use in Germany [6].
The Dutch response test rig was built in a sea shipping container [7]. It is operated with a reversible heat pump, and thus can be run in either heating or cooling mode. The heat pump generates a supply of warm or cold fluid, which is used to maintain a certain temperature difference between fluid entering and leaving the borehole. The test rig may be used for response tests on single or multiple boreholes.
There are a number of response test devices in operation in USA. The first one described in the literature was developed at Oklahoma State University in 1995 [8]. Several commercial thermal response test devices have been developed. An Oklahoma company has developed a number of test rigs, starting with a version mounted on a trailer, and progressing to versions that fit in airline-shippable crates. Another Oklahoma company has developed a unit that fits in a medium-sized suitcase. Other commercial units have been fabricated by companies in Nebraska, Texas and Tennessee. Test conditions vary widely throughout the USA and hundreds of tests have been made for commercial clients, without the results being published, however more that 15 publications written between 1998-2000 are available [1].
Switzerland has two mobile test rigs in operation since 1998 for measurements of boreholes and energy piles. A British version of thermal response test apparatus was constructed by in Cornwall in the summer of 1999. France has shown recent interest in a test facility in their communication with Switzerland and technology transfer has been discussed. A Japanese company has prepared a test rig, similar to one of the Swiss units.

3. OPERATIONAL EXPERIENCE

Test cost is related to test length. The measurement time necessary for obtaining sufficient data for a reliable analysis has been discussed much since the beginning of response test measurements. Austin, et al. [9] found a test length of 50 hours to be satisfactory for typical borehole installations. Gehlin 10] recommends test lengths of about 60 hours. Smith and Perry [11] claim that 12-20 hours of measurement is sufficient, as it usually gives a conservative answer, i.e. a low estimate of thermal conductivity. Comparison of tests of different duration are published by Austin, et al. [9] and Witte, et al. [7].
Operational experiences of the test units have shown some sources of error that can affect the results. These include heat leakage to or from the air, fluctuations in electrical power, and inaccurate measurements of the undisturbed ground temperature. In addition some more or less unpredictable disturbances have been reported such as blocked U-tubes, power failure and fluid leakage. Uncontrolled heat losses or gains to or from the environment due to insufficient thermal insulation

cause problems in the analysis of the experimental data. This problem may be overcome by adequate insulation of the experimental apparatus and piping. It is helpful to measure ambient air temperatures during the test so that the effects of changing ambient air temperature may be investigated. It may be possible to correct for these effects with some analysis procedures if a good estimate of the heat loss or gain can be made.

Fluctuations in the electrical power supply can cause problems with line source analysis, which usually assumes a constant heat injection rate. Suggetsed solutions are; using a significantly oversized generator, control the temperature difference directly, while maintaining a constant flow rate or to control the temperature difference while measuring the flow rate, so as to maintain a constant heat injection or extraction rate, or using an analysis procedure that can account for fluctuating power.

Field observations have suggested that there is a groundwater aspect on the borehole performance [10,12]. Some theoretical studies have been published on the subject [13-15].

4. ANALYSIS METHODS

Different mathematical models - analytical and numerical - are used for the evaluation of response test temperature data. The different models require somewhat different sets of input data

Analytical models, such as the line source and cylinder source adopt the analytical solution of the heat transfer problem between the borehole and the nearby infinite region. They require several simplifying assumptions regarding the geometry of the borehole and heat exchanger pipes. For the purpose of the thermal response test evaluation, the heat flow to or from the borehole may be represented as an infinitely long heat source or sink in the ground with negligible influence of heat flows in a direction along the borehole axis. In the ground outside the borehole it is common practice to assume that the thermal process depends only on the radial distance from the borehole axis. The one- or two-dimensional heat flow process from the circulating fluid to the borehole wall is assumed to be represented by a thermal resistance that characterises the temperature loss between heat carrier fluid and borehole wall. Some models also include the thermal mass of the materials in the borehole.

Ingersoll and Plass [16] applied the line source model to design of ground loop heat exchangers. Mogensen [2] proposed to use the borehole similar to the probe to estimate the ground thermal conductivity from an experimental field test. This method is now commonly used for thermal response test evaluation in Europe. In practice, researchers have made use of this approach in somewhat different ways although they essentially follow Mogensen.

The cylinder source model, of which the line source model is a simplified variation, may be used for approximating the BHE as an infinite cylinder with a constant heat flux. The heat exchanger pipes are normally represented by an ”equal diameter” cylinder. Carslaw and Jaeger [17] developed analytical solutions with varying boundary conditions for regions bounded by cylinder geometry. Deerman and Kavanaugh [18] and Kavanaugh and Rafferty [19] describe the use of the cylinder source model in designing ground loop heat exchangers. The effective thermal conductivity (and diffusivity) of the ground formation is computed by reversing the process used to calculate the length of the ground loop heat exchanger.

Numerical models can be designed to handle detailed representations of the borehole geometry and thermal properties of the fluid, pipe, borehole filling and ground, as well as varying heat transfer rates. The more extensive set of required input data often make these models more difficult and time-consuming to use than the analytical methods, which sometimes may be implemented as simple spreadsheet applications. Berberich et al. [20] describe a response test type of measurement in groundwater filled ducts in water saturated clay stone where temperature sensors were placed along the borehole wall. The measured data were analysed with both an analytical line source model and a numerical two-dimensional finite difference model using parameter estimation with ground thermal conductivity and volumetric heat capacity as variables. Shonder and Beck [21] developed a parameter-estimation-based method, which is used in combination with a one-dimensional numerical model. This model is similar to a cylinder-source representation, in that it represents the two pipes of the U-pipe as a single cylinder. However, it adds two more features - a thin film that adds a resistance without heat capacity, and a layer of grout, which may have a thermal conductivity and heat capacity different from the surrounding soil. This model accommodates time-varying heat input. A transient two-dimensional numerical finite volume model in polar co-ordinates for response test evaluation is reported in [8,9]. The geometry of the circular U-pipes is approximated by "pie-sectors" over which a constant flux is assumed. The convection resistance due to the heat transfer fluid flow inside the U-pipes is accounted for using fluid properties through an adjustment on the conductivity of the pipe wall material. The model was improved by introducing a boundary-fitted grid system that is more flexible and better represents the U-pipe geometry [22].

6. CONCLUSIONS

Since the introduction of mobile thermal response tests in 1995, the method has developed and spread in North America and Europe. With the exception of the Dutch system and the Aetna rig, which can impose either heat injection or heat extraction, all of the systems rely on imposing a heat injection into the ground. A variety of data analysis models have been developed. Various applications of the line source approach are used because of its simplicity and speed. The line source theory is the most commonly used model for evaluation of the response test data in all eight countries, and is dominant in Europe. Numerical models coupled with parameter-estimation techniques are used mainly in USA. Thermal response tests have so far been used primarily for in situ determination of design data for BHE systems, but also for evaluation of grout material, BHE types and groundwater effects.

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Appendix 1 Summary of Experimental Apparati State of the Art December 2001 [1].

Reporting Country	Canada	Germany[1]	Netherlands	Norway	Sweden	Switzerland[2]	Turkey	United Kingdom	U.S.A.[3]
Configuration	Trailer	Trailer	Container	Trailer	Trailer	mobile	Trailer	Cart, 2-wheel	Trailer
Heat Injection (kW)	3.2	1-6	0.05-4.5	3-12	3-11	3-9	3-12	3-6	0-4.5
Heat Extraction(kW)	--	--	0.05-4.5	--	--	--	--	--	--
Power Control	None	Manual, six levels	Continuously variable with controlled ΔT	Manual, four levels	Manual, three levels	semi-manual, three levels	Manual, four levels	Manual, two levels.	Manual, continuously variable rate.
Flow Rate (l/s)	0.75 (est.)	0.28	0.14-0.83	0.5-1.0	0.5-1.0	variable	0.5-1.0	0.25-1	0.2 (typical)
Circulating Fluid	Water / Prop. Glycol	Water	Water Water/glycol	Water / Prop. Glycol	Water / Prop. Glycol	Water	Water	Water	Water
Temperature sensors	Not reported.	PT100	PT100	Thermocouples	Thermocouples	PT100	Thermocouples	Thermistors	Thermistors
Reported accuracy: temperature sensors	Not reported.	Not reported	±0.07 K	±0.2 K	±0.2 K	0.1	±0.2 K	±0.1 K	±0.1 K
Power sensor	Not reported.	Not reported	Not reported	Watt transducer	Watt transducer	not reported	Watt transducer	kWh meter (pulse output)	Watt transducer
Reported accuracy: power measurement	Not reported.	Not reported	Not reported	±2%	±2%	not reported	±2%	Not reported	±1.5%
Flow sensor	Estimated from ΔP.	Not reported	MagMaster	Volumetric flow meter	none	not reported	Volumetric flow meter	Electromag-netic	Volumetric flow meter
Reported accuracy: flow sensor	Not reported.	Not reported	0.2-0.9 %	±3%	--	not reported	±3%	Not reported	±2%

[1] There are three known test units in Germany; only one (UBeG) is described in this column.
[2] There are two known test units in Switzerland; only one (EPFL) is described in this column.
[3] There are a number of test units in the USA; the one described in this column is the only one for which specifications are published.

Appendix 2. Summary of Measurements State of the Art December 2001 [1].

Reporting Country	Canada	Germany	Netherlands	Norway	Sweden	Switzerland	Turkey	United Kingdom	U.S.A.
First year of operation	2000	1999	1999	1998	1996	1998	2000	1999	1995
Number of test rigs	1	3	1	1	1	2	1	1	>10
Total number of tests	2	> Ca. 35[4]	Ca. 20[5]	Ca. 50	Ca. 35	7	2	Ca. 6	>300
Measured ground types	Hard rock, Slate	Unconsolidated sediments (sand, silt etc.), Sediments (Marl, Shale etc.)	Clay, sand, peat, shale, mudstone, sandstone, chalk	Hard rock, Shale	Hard rock, Shale, Sedimentary	Molasse sediments	Sedimentary	Hard rock, shales, clays, mudstones, coal bearing measures, limestone	Sedimentary, clay, shale
Measured BHE Backfill material	Groundwater	Grout, Sand	Groundwater Bentonite grout, sand, ground material, bentonite/cement grout	Groundwater	Groundwater, Sand	Grout (BHE)	Groundwater	High solids bentonite	Bentonite grout, thermally enhanced grout, pea gravel, sand
Measured BHE types	Single U-tube	Single U-tube, double U-tube Energy piles	Single and double U-tube, concentric	Single U-tube	Single U-tube, double U-tube, concentric	Double U-pipe , Energy piles (EP)	Single U-tube	Single U-pipe with geoclips	Single U-tube, double U-tube.
Typical borehole depth	55-91 m	26-117 m (min. pile 7 m, max 250 m)	30-100 m	120-200 m	100-150 m	150-300 m (BHE) < 30 m (EP)	150 m	50-70 m	60-120 m
Typical borehole diameter	150-164 mm	150-160 mm	50-300 mm	115-140 mm	110-115 mm	150 mm (BHE) ~240 mm (EP)	150-200 mm	125-150 mm	85-150 mm

[4] UBEG and AETNA ca. 15 tests each from 1999 to 2002
[5] Tests performed in Netherlands, Belgium and UK