THERMAL RESPONSE TESTS OF BOREHOLES
- RESULTS FROM IN SITU MEASUREMENTS

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ABSTRACT

During the last year thermal response tests of boreholes in rock were carried out with a mobile test equipment (TED) in several duct stores for heating and/or cooling. Most of the tests were made for the Swedish telephone company TELIA that is constructing a great number of direct cooling systems for their telephone switching stations. The size of these duct systems in the different plants tested, varies from 4 to 60 boreholes, drilled in hard rock - mostly granite and gneiss. This paper summarises results and experience from the measurements.

1. INTRODUCTION

The main part of the construction cost of a borehole heating/cooling system is the drilling cost and the pipe system. More elaborate optimisation of the systems would reduce the number of required boreholes, which would consequently reduce the cost and make the systems more economically competitive.

The heat transfer capacity of a borehole system is crucially dependent on the thermal resistance between the heat carrier and the surrounding rock. A lower thermal resistance means that a smaller temperature difference is required between the bedrock and the heat carrier, for a given heat power. This thermal resistance is seen as a temperature drop between 1/ the heat carrier fluid and the borehole wall, and 2/ the borehole wall and the surrounding rock. These temperature losses are dependent on the thermal properties of the pipe materials and borehole filling, shank spacing, flow conditions, etc. (in the borehole) and on the thermal conductivity of the bedrock, fractures, ground water flow, etc. (outside the borehole).

The thermal response test - TED measurements - means in situ measurements of the heat transfer capacity of boreholes for energy injection or extraction. The evaluated results include thermal properties of the ground and the borehole, but also the effect of factors that are difficult to estimate, e.g. natural convection in the boreholes, asymmetry in the construction, etc. By testing one borehole and evaluating its capacity in situ, the design of the borehole system can be optimised regarding the total geological, hydro-geological and technical conditions at the location. Consequently, there are two reasons for performing such measurements:

1. To obtain reliable heat transfer data for dimensioning
2. To study new ground heat exchangers

1.1 Measurement Equipment

A mobile thermal response test equipment, TED, was constructed at Luleå University of Technology in 1995. The equipment consists of a pump, a heater and temperature sensors for measuring the inlet and outlet temperatures of the borehole. It is set up on a small trailer and easily transportable. The test is fully automatic including the recording of measured data and takes 4-5 days to execute. The results are easily evaluated from the data. Plotting the mean fluid temperature versus time as in Fig 1 the thermal conductivity is proportional to the inclination of the graph. The temperature level of the graph is proportional to the thermal resistance of the borehole.

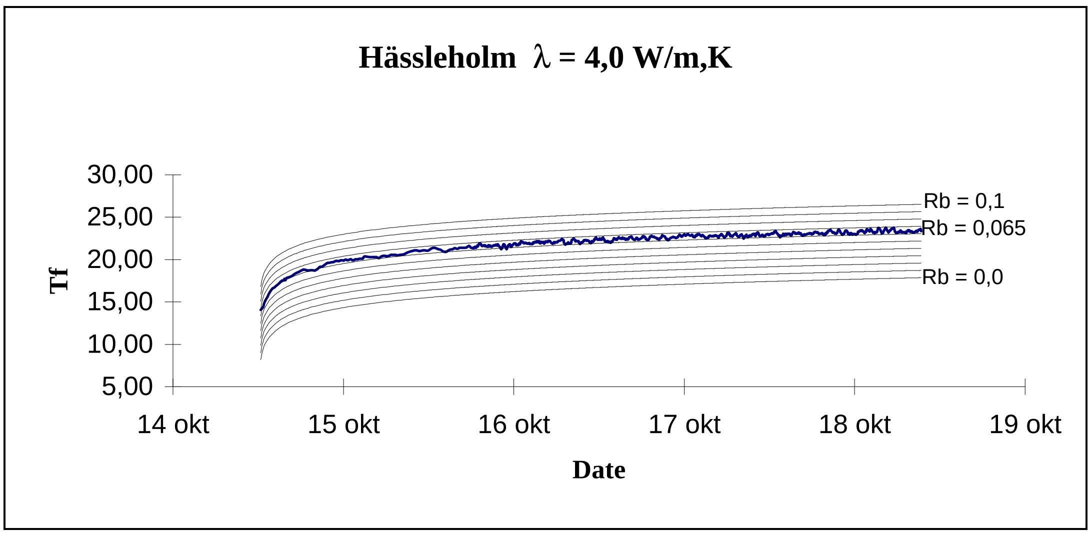

Fig 1 Example of measured mean fluid temperature in borehole compared to calculated mean temperatures for thermal conductivity of 4 W/m,K at different thermal resistance.

The borehole pipes are connected to the pipe ends on the trailer. The pipes are filled with heat carrier fluid, which is pumped through the system. As the fluid passes through the heater it is heated at constant power. Temperature sensors measure the fluid temperatures at the inlet and outlet pipes and the temperatures are recorded along with date and time by the logger at a selected time interval, usually 2 minutes. The equipment is powered by electricity and the prototype uses two power levels for the heater. Including the contribution from the circulation pump, the two power levels are 6.4 kW and 11 kW. For an average 150 m borehole, the heater causes a temperature rise in the borehole of 10^{o}C and 15^{o}C respectively during a normal 4-5 day response test with a flow rate in the pipes of about 1 l/s. The total cost for the equipment was USD 10,000 (Gehlin & Nordell, 1997). A more detailed description of the measurement equipment and of the analysis procedure is given in Eklöf and Gehlin (1996).

Date, time and inlet- and outlet temperatures are the minimum logged data requirements for the evaluation of a response test. It is however recommended to record ambient temperature, hydraulic pressure in the pipes, flow rate and power demand to obtain a more complete set of data to check the measurements. These measurements will be included in the new version of the prototype.

2. PERFORMED TED MEASUREMENTS

2.1 TELIAs direct cooling system

The main part of the TED measurements have been performed at duct systems for direct cooling of telephone switching stations. The Swedish telephone company TELIA is gradually replacing their cooling machines (CFC) with the more environmentally friendly direct duct cooling systems in hard rock. The total energy savings from the use of this system is estimated to 40% and the savings in electrical energy is 80% (Hellström & Gehlin, 1997).

The telephone switches operate at their optimum at a temperature of around 25^{o}C but generate a constant heat power which must be removed. Therefore TELIA has developed a new low temperature heat exchanger which is well suited for connecting to duct systems as a cold source.

The heat from the telephone switches raise to the ceiling by natural convection forces and are fanned through the low temperature heat exchanger. There the warm air meets the cold fluid from the boreholes, and the cooled air is then let out at the floor level. The cold fluid from the boreholes is circulated with a circulation pump through U-shaped loops of plastic piping in the groundwater filled boreholes (ducts). The fluid transfers the heat to the surrounding hard rock, which has a natural undisturbed temperature of about 8^{o}C in Sweden. The duct systems are sized so that the maximum outlet temperature from the boreholes will not exceed 19^{o}C.

Several of the direct cooling duct systems are constructed for continuous operation and can therefore use water as heat carrier. In systems combined with direct air cooling in winter time so that the ducts only will operate seasonally, some frost preventive additive must be used (e.g. glycol, ethanol etc.).

The duct systems are all constructed with single U-pipe installations, but lately an increased interest for double U-pipes has shown from TELIA. Double U-pipes result in lower thermal resistance and lower hydraulic loss and thus lower energy losses. Recently performed field experiments have shown that the thermal resistance for double U-pipe systems is 3-4 times lower than for single U-pipe systems, which corresponds to experience from laboratory experiments at Lund University of Technology (Hellström 1998). An overview of the size of the measured cooling systems is shown in Table 1.

Table 1 Description of direct cooling duct systems for TELIA

Location	Number of boreholes	Active depth (m)	Maximum Cooling Load (kW)	Annual Cooling Load (MWh)
Drevikstrand	4	155	20	173
Ängby	6	154	27	237
Oskarshamn	4	161	30	259
Hässleholm	19	150	105	185
Linköping	7	157	45	80
Norrköping	20	157	108	192
Ludvika	5	149	35	49
Örebro	60	199	200	173

2.2 Results from measurements

The cooling systems where measurements have been performed are located in south Sweden. The ground is typically granitic with a high groundwater level. At the locations the groundwater level varied between 1-18 m below ground surface, with a typical level of 3-4 m. The undisturbed ground temperature is typically about 9^{o}C but vary slightly due to latitude etc. Table 3 summarises the physical data for the systems. The measured boreholes have depths between 115-161 m, except for the site in Örebro (197 m), where a new type of water driven down-the-hole well drilling equipment has been tested, allowing the boreholes to be drilled much deeper than today's standard (Nordell et al, 1998). The borehole diameter varies between 115-160 mm.

The basic results from the measurements are over-viewed in Table 2. A remarkably high undisturbed ground temperature is observed in Oskarshamn and Ludvika. In Oskarshamn the elevated ground temperature is likely due to the duct system being located on a hill in the centre of the town, and surrounded by heat sources such as large houses and streets with considerable traffic.

For the case of Ludvika, the measurement was disturbed partly due to measurements being done too short time after the drilling of the hole, and also by on-going drilling in an adjacent hole. The results from the Ludvika measurement could not be used for dimensioning, but however, the results are interesting not only to show the influence of the heat from the drilling, but even more to confirm the importance of convection in the boreholes. As two strongly permeable layers were reported from the drilling, and drilling was performed in a nearby borehole during the measurements, there is reason to suspect a highly elevated forced groundwater flow through the measured borehole. This is observed as an extremely high effective thermal conductivity, giving the impression that the rock is highly conductive. It is however the groundwater flow that transports much of the heat and causes this effect.

Table 2 Physical data for measurements

Site	Rock	Fluid	Groundwater (m)	Active borehole depth (m)	Borehole diameter (mm)
Drevikstrand	granite	Etylenglycol	3	160	140
Ängby	granite	Etylenglycol	7	132	115
Oskarshamn	granite	Ethanol	4	161	135
Hässleholm	granite	Water	18	126	160
Linköping	granite	Water	5	115	160
Norrköping	granite	Water	3	157	115
Ludvika	granite	Water	3	117	140
Örebro	granite	Water	1	197	115

From the other locations the thermal conductivity typically varies between 3.2-4.2 W/m,K. This should be compared with the typical values for Swedish granite, which is in the interval 3-4.5 W/m,K (Sundberg, 1988). The high values for Drevikstrand and Ängby are notable, and will be analysed further.

Thermal resistance varies between 0.04-0.10 K/(W/m). Standard value for dimensioning of duct systems has so far been 0.10 K/(W/m), but the TED measurements indicate a slightly lower resistance to be expected. The reason is probably natural convection in the boreholes, which increases the heat transfer.

Table 3 Results from measurements

Site	Active borehole depth (m)	Undisturbed ground temp (^{o}C)	Maximum measured temp (^{o}C)	Heating Load (kW)	Measured λ (W/m,K)	Measured Thermal Resistance (K/(W/m))
Drevikstrand	160	9.2	21	11	5	0.10
Ängby	132	9	23	11	5.5	0.08
Oskarshamn	161	10.5	18	6.4	3.2	0.05
Hässleholm	126	8.7	23.4	11	4	0.08
Linköping	115	8	24.7	11	3.4	0.04
Norrköping	157	8.5	21.3	11	3.5	0.05
Ludvika	117	11*)	16.3*)	6.4	11.5*)	0.05*)
Örebro	197	9	16.2	6.4	4.2	0.07

*) The measurements were disturbed by on-going drilling in an adjacent borehole

3. DISCUSSION

3.1 Measurements

The field measurements indicate that the thermal resistance in the boreholes is lower than expected from laboratory experiments. This means that in field there are factors that decrease the resistance and that do not exist in laboratory environment. The explanation could not be found in pure natural convection due to temperature gradients within the borehole, as this would occur in the same way in laboratory.

A possible explanation could be the volume expansion of the heated water in the borehole. In general the temperature in a borehole is raised 10-15^{o}C during a response test. With a volume expansion for water of 0.25% (Franks, 1972), this would give an elevation of the water level in a 150 m borehole of about 0.4 m. This elevated groundwater level would cause a convective movement in the ground, as the water is tapped off in fractures at the top of the borehole at the same time as cold water is pressed into the boreholes from fractures deeper down. This large scale natural convection would not show in laboratories or in a theoretical perfectly sealed borehole. Such perfectly sealed boreholes are, however, not very likely to be found in nature. A closer investigation of this theory will be done during 1998.

The Ludvika measurement tells that groundwater flow through fractured rock does influence the heat transfer in boreholes. The elevated convection in the borehole due to the drilling in an adjacent borehole shows that groundwater flow can improve the effective thermal conductivity and heat transfer in the borehole.

Experience from the measurements tells that a correct estimation of the undisturbed ground temperature at a location is important, since this parameter greatly affects the calculations. The influence on the ground temperature from permanent buildings and roads as heat sources may be of interest to investigate further.

It is important that the test equipment is well insulated to prevent the influence from changes in ambient temperature, which could give a wrong impression of the amount of heat transferred to the ground.

3.2 Planned measurements

During 1997 a series of measurements have been performed at the borehole heat store in Luleå (Nordell, 1991). More measurements will be executed during 1998 and the experiment schedule is shown in Table 4. Measurements and analysis are under procedure at the time for this paper being written, and will be thoroughly reported in a licentiate thesis later in 1998.

The main objectives of the experiments are to further investigate and analyse the effects of natural and forced convection in the boreholes, and tests will be done with external circulation pumps descended into boreholes. Different fillings and installation performances (e.g. single U, double U, coaxial, open) will be compared on a technical as well as economical basis, and also experiments with freezing in boreholes are planned.

The results from the measurements will in a later stage be used to study the transient period during the first hours of measurements. This will give valuable information about the thermal behaviour of the volume within the borehole wall and can be of use for the design of systems with intermittent operation.

Table 4 Experimental scedule for measurements in Luleå

Installation Type	Arrangement	Comments
Single U-pipe	Simple External Convection Filled Frozen	Performed Performed Planned Planned
Double U-pipe	Simple External Convection Filled	Performed Planned Planned
Open	Simple External Convection	Planned Planned
Coaxial	Simple	Planned

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