

QUALITY CONTROL OF BOREHOLE HEAT EXCHANGER SYSTEMS

M. Reuß, M. Proell

Bavarian Centre for Applied Energy Research (ZAE Bayern)
Division 1: Technology for Energy Systems and Renewable Energies
Walther-Meißner-Str. 6, D-85748 Garching, Germany,
e-mail: reuss@muc.zae-bayern.de

R. Koenigsdorff

Biberach University of Applied Sciences
Karlstr. 11, D-88400 Biberach
e-mail: koenigsdorff@hochschule-bc.de

ABSTRACT

The vast growing market for borehole heat exchangers (BHE's) requires great efforts of quality assurance in design and construction. Within a research project funded by the German Federal Ministry of Economics and Technology a consortium consisting of the University of Applied Sciences at Biberach (UASB), the University of Karlsruhe (EIFER, GI) and the Bavarian Centre of Applied Energy Research (ZAE Bayern) is investigating subjects related to quality management of BHE's.

For proper design of BHE's reliable data on thermal properties of the underground determined by the Thermal Response Test are essential. New measurement techniques and improved evaluation models are developed.

The design tool GEOSYST developed by (UASB) which considers the whole system, the building as well as the ground source in one step will be enhanced further and validated.

Borehole grouting is an important issue from the environmental point of view. The sealing properties of different grouting materials are investigated under realistic operating conditions.

1. INTRODUCTION

The continuous growth of the market for ground source heat pumps with borehole heat exchangers (BHE's) and borehole storage systems for heating and cooling requires great efforts of quality assurance in design and construction of BHE's to guaranty a sustainable and ecologically beneficial development of this technology. Within a research project funded by the German Federal Ministry of Economics and Technology a consortium consisting of the University of Applied Sciences Biberach, the University of Karlsruhe (EIFER, GI) and the Bavarian Centre of Applied Energy Research (ZAE Bayern) who is also coordinating the project, is investigating several subjects related to quality management of BHE's.

A major focus is put on further development of the Thermal Response Test (TRT) as a useful instrument for site investigation to gain reliable data for a proper system design from the technical and economic point of view. Intensive research combined with exchange of experiences on an international level within the IEA ECES Annex 21 should improve the technology but also promote the application worldwide.

In the early project development often the decision is made towards the heating system and the heating and/or cooling source. A software tool to assist this decision making and later for

system design which considers the building and the underground system could be helpful for promotion of these techniques. GEOSYST tries to fill this gap.

In the construction phase borehole grouting is an important issue from an environmental point of view. Water authorities are afraid of connecting aquifers and pollution of aquifers by leaking borehole heat exchangers operated with antifreeze and corrosion inhibitors.

This research project deals in several subprojects with different problems which affect the system quality. A selection of it is discussed in this paper.

2. FURTHER DEVELOPMENT OF THE THERMAL RESPONSE TEST

Three major subjects which were identified from practical experiences in more than 100 tests carried out will be investigated within this project:

- Development of improved evaluation models
- Evaluation of the TRT with respect to geological layers
- Investigation of the influence of ground water

Theoretical work and models will be validated with experimental results from tests carried out at pilot drillings at four locations with different geological conditions. Additionally, cores from these pilot drillings will be analysed in detail by the Geological Institute of Karlsruhe University.

2.1 Evaluation Models

In most cases Kelvin's Line Source Model is used for evaluation which limits the accuracy of the results. In some cases the conditions required for application of the line source model like constant heat flux etc. cannot be met. Thus improved models combined with numerical methods of parameter identification can be an appropriate solution.

The common method, the single step pulse test with constant heat flux, was modified by using a 'dynamic' heat flux which was varied in several steps as shown in Fig. 1. A first evaluation with a 1-dimensional radial symmetric model shows good agreement with the measured data. Parameter estimation routines are used to determine also the heat capacity of the underground.

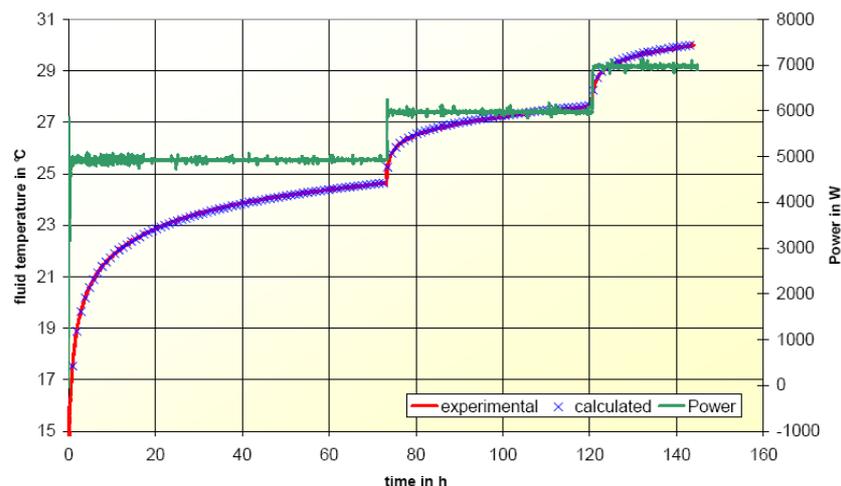


Fig. 1: Temperature response - comparison of measured and calculated values

The actual numerical model will be modified to also describe the decay of temperature in the ground. As a side effect this also allows to evaluate tests with interrupted heat flux e.g. cause by an electric power cut.

2.2 Evaluation With Respect to Geological Layers

Additionally to this dynamic test vertical temperature profiles after the test are recorded with a submersible data-logger (Nimo-T (Forrer et al., 2008), see Fig. 2). The actual depth is determined from the recorded pressure while the temperature of the fluid is measured. The density of this device is very close to the fluid in the pipe to gain a rather low velocity of descent. The vertical temperature profiles taken after the TRT (after 2 ¼ h, 5 ¾ h and 28 h) show a significant fluctuation at different depths. These fluctuations indicate variations of the thermal conductivity in the geological layers. The fast temperature decay between 22 m and 32 m may be due to a significant ground water flow.

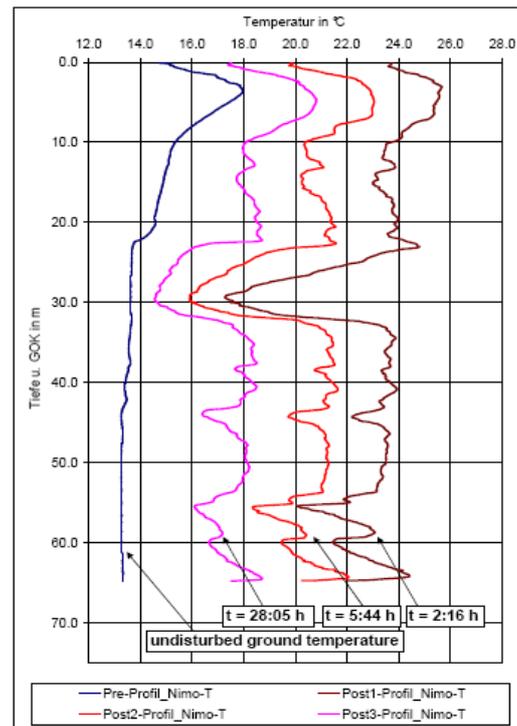


Fig. 2: Submersible temperature and pressure data logger and Fig. 3: Vertical temperature profiles in the fluid of the BHE at 3 different dates after the test

Detailed experimental investigation of layer related TRT, the so called enhanced TRT, will be carried out at pilot boreholes which are equipped with several temperature sensors and glass fibre optic temperature measurement. Additionally the cores are analysed regarding e.g. water content and thermal conductivity at the laboratory of the Geological Institute at the University of Karlsruhe.

At a first 100 m deep pilot borehole in Dinslaken different sensors for measuring the vertical temperature profile were tested and two TRT methods were carried out. The temperature profile measurement of the undisturbed ground with three different methods (purging, Nimo-T and fibre optics) shows a good agreement (Fig. 4) if the values from 15 m downwards are considered. The deviation of the mean values (11.82 °C from purging) for 15 – 100 m is below 0.07 K. From the fibre optical measurement and also the Nimo-T it can be seen that there are significant influences from ground water (upper 10m) and the ambient in the upper part of the borehole. The shape of the Nimo-T curve may also be influenced by heat capacity effects which have to be analysed in more detail. In principle all three methods are appropriate to determine the undisturbed ground temperature before a regular TRT. For analysing the temperature profile after a test only the fibre optical measurement and the Nimo-T give useful values.

The first enhanced TRT was done by the company GTC Kappelmeyer using electric heating by a special cable installed in the borehole beside the pipe of the BHE and the glass fibre optic temperature measurement (Heidinger et al., 2004). In Fig. 5 the ground conductivity values gained from this test are shown in comparison to the values measured at the core samples. Looking at the average λ -value the one obtained from the core is 2.07 W/(m*K) and thus slightly higher than the one from the enhanced TRT with 1.87 W/(m*K). The TRT performed by ZAE delivered an effective λ -value of 2.31 W/(m*K). The layer related evaluation of this last test is not yet finished the results will be given in the presentation.

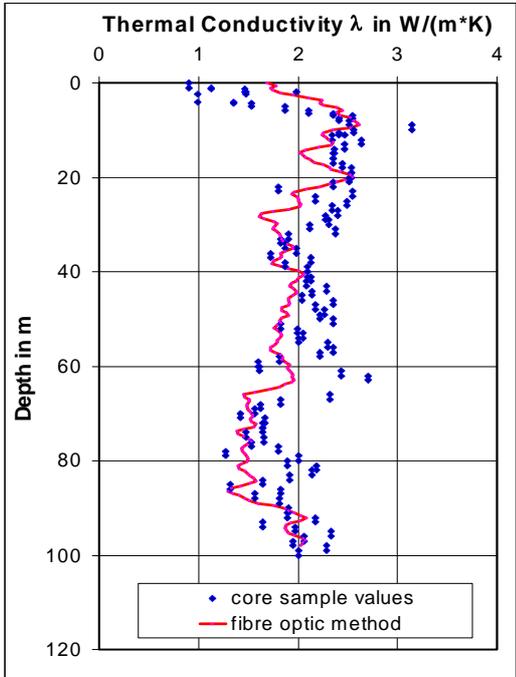
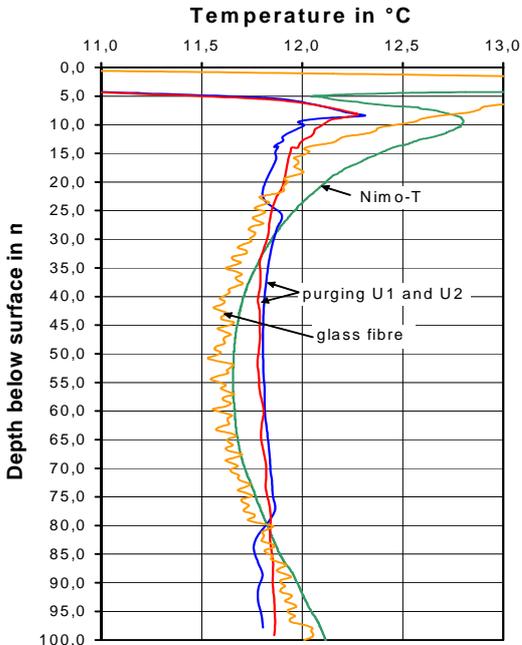


Fig. 4: Comparison of temperature profile measurement (different methods)

Fig. 5: Enhanced TRT results compared to λ -values from core samples

2.3 Ground Water Influence

As shown in Fig. 3 ground water especially at higher speed has a significant impact on the heat transfer from ground to the fluid and vice versa. In a regular TRT evaluated with the line source model the result is a high value of the effective thermal conductivity of the ground.

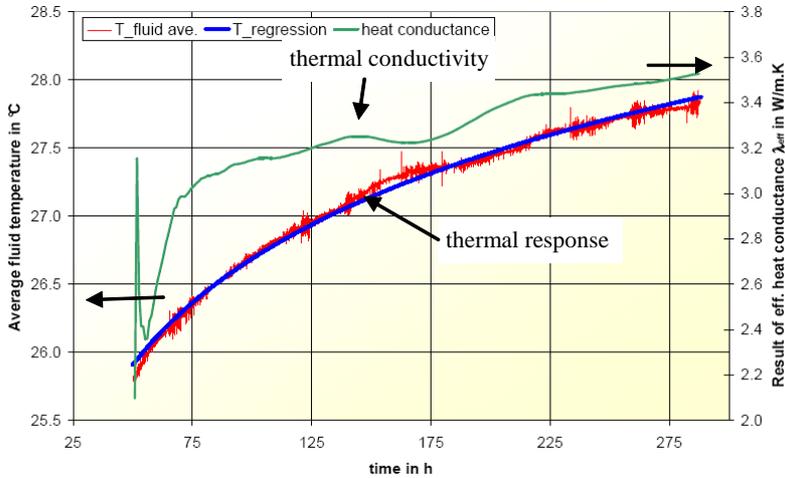


Fig. 6: Thermal response with ground water influence

If for the evaluation of the conductivity the starting time is kept fixed and the evaluation interval continuously enlarged the result is no longer a constant value but increases with time as shown in Fig. 6. In case of ground water the thermal transport process is not only conduction but also convection. Actually these two processes can not be separated with the described test and evaluation method.

For more detailed investigation one of the pilot boreholes together with three observation wells will be built at the University of Applied Sciences at Biberach. At this location there is an aquifer which can be used for experiments.

3. DESIGN TOOL GEOSYST

Besides site investigation a proper system design requires appropriate and reliable tools for simulation of the system. Within this joint research project, the University of Applied Sciences at Biberach (UASB) further develops the design tool GEOSYST (Koenigsdorff et al., 2006). This is a software tool that allows the design of vertical borehole heat exchanger (BHE) fields used for heating and cooling of office buildings.

The software calculates the heating and cooling energy demand of a given building on a monthly basis similar to the German calculation method used for demand based energy certificates according to the EU guideline. With the building's monthly heating and cooling energy demands calculated, the model determines the required borehole length within a given borehole field configuration. Since the coefficient of performance of the heat pump strongly depends on the necessary temperature rise between the heat source and the heat sink temperature, the heat extraction rate (heat input to the evaporator of the heat pump) is calculated iteratively in conjunction with the fluid temperature in the boreholes. This calculation is done for the first year of operation as well as for quasi-steady-state conditions after a large number of operation years by using the well known g-function method.

Besides some improvements and adaptations of the building and the heat pump model, the main task in this project is to incorporate a transient three-dimensional finite-volume-model into GEOSYST to be able to deal with different and arbitrary geothermal heat source systems. The model uses a multi-grid and a hybrid approach to account for the different spatial resolutions necessary. The coarse main grid which is used to calculate long-term and far-field effects and interactions within a large region (e. g. a whole borehole field) is based on Cartesian coordinates. Short-term and local effects, e. g. heat transfer of a single borehole or pipe within the ground, are either calculated with a finer grid (which might be of a boundary-fitted type) or with analytical approaches (e. g. form factors). Preliminary results of a first prototype are shown in Fig. 7.

The evaluation of measured data from a Thermal Response Test is envisaged to be a further application of the model. It is necessary to use an identical calculation method and software for determining the soil and borehole properties of a geothermal system from a Thermal Response Test and for system design. It is expected that this will facilitate and improve the inclusion of Thermal Response Test results into the geothermal system design process and thus will result in a higher quality of geothermal systems design and operation.

4. INVESTIGATION OF GROUTING MATERIALS

One of the major concerns of German water authorities regarding BHE's is the sealing of the borehole by proper grouting. From their point of view the major function of the grout is sealing in vertical direction to avoid connection of two aquifers and to seal the borehole in case of leaking BHE pipes to avoid pollution of aquifers by heat transfer fluids with antifreeze like

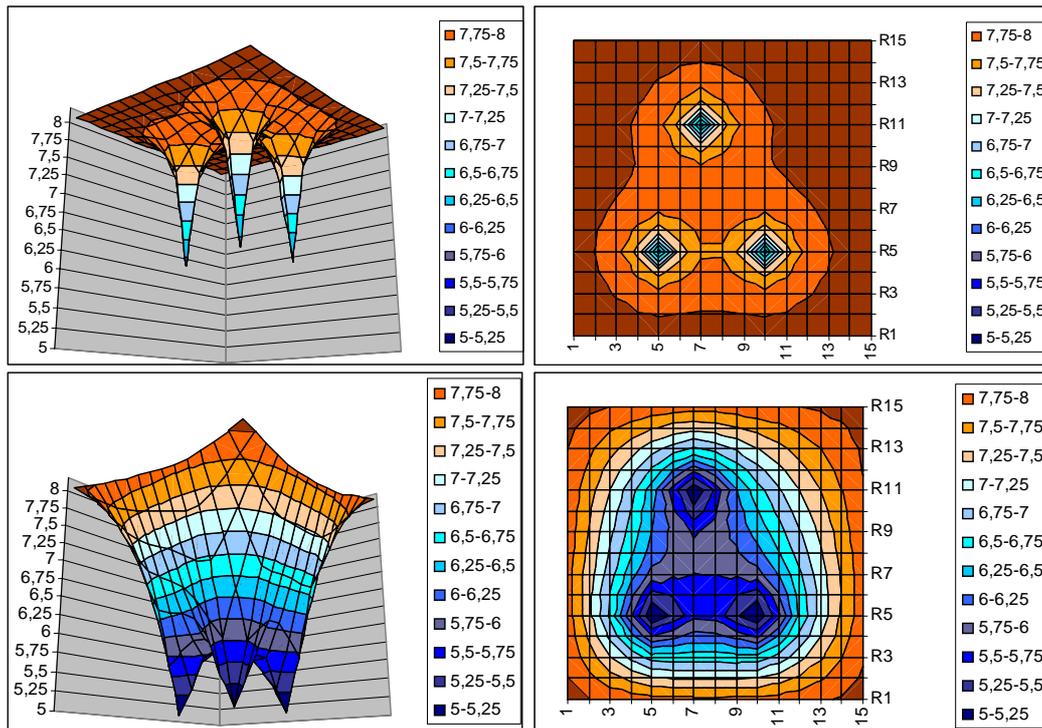


Fig. 7: Calculation results of the prototype of the 3D geothermal finite-volume-module under development for a field of three boreholes (upper row: borehole temperature after 3 months of operation, lower row: after 30 years of operation)

glycol and corrosion inhibitors. Today several materials especially developed for this application by industry are available on the market. In Germany we found at least 15 such grouts.

The principal task of the grouting is the sealing of the borehole and the provision of good thermal contact between the pipes and the underground. All those materials are typically based on clay minerals (e.g. bentonite), cement and stone dust; in some cases additives like graphite increase the thermal conductivity. The material is mixed with water in an appropriate mixing machine and pumped down the borehole through a separate grouting pipe. The borehole is filled from the bottom without retrieving the grouting pipe to avoid air inclusion and bridging. The filling pipe will remain in the borehole as it is required by the VDI 4640 Guidelines (part 2).

As heat pump operation runs also at temperatures below zero freezing and thawing of the grout has to be considered. Even after many such freezing and thawing cycles the sealing properties have to remain unaffected, mechanical strength is not a primary issue. Typical test procedures used for testing of concrete are not applicable because of the different requirements. While concrete has to maintain its strength this is not necessary for the grout. Additionally the grout in the borehole at a certain depth is exposed to high pressure which reduces the risk of creating cracks by freezing and thawing which open a routeing path for the ground water movement from one aquifer to another. Because of this risk of connecting two aquifers this subject will be investigated within this project.

First of all an appropriate hydraulic parameter has to be found to analyse and quantify the impact of freezing and thawing of such grouting materials. The best choice seems to be the coefficient of permeability of the material which can be measured with triaxial cells. For the material itself the standard triaxial cell experiment as shown in Fig. 8 is sufficient.

In the case of BHE's the whole system of pipes embedded in the grout has to be considered and this under real operating conditions. Therefore a large experimental setup is developed (Fig. 9) which allows this measurement at a model 'borehole' with 150 mm diameter and a length of at least 2.5 m. The BHE pipes (2-U-BHE) are mounted in a plastic pipe with 150 mm diameter as the outer wall of the borehole. To gain contact between this 'borehole' plastic pipe and the grout it will be covered with a sand layer which is bond to the pipe. The whole experiment is set under pressure to simulate a depth of e.g. 50 m. Through the BHE pipes fluid is circulated for heating and cooling of the grout. It is planned to run freezing thawing cycles according to realistic operating conditions which are determined by system simulation of e.g. a ground source heat pump.



Fig. 8: Standard triaxial cell experiment for determination of the coefficient of permeability

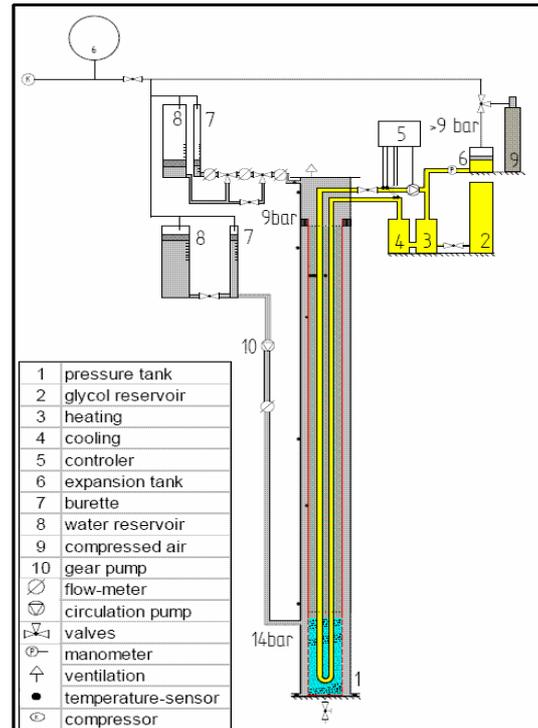


Fig. 9: Design of the permeability test cell for grouted BHE's

At the present several industrial grouting products are analysed in the standard triaxial cell (DIN 18130-1, 1998). These results serve as reference values for the following large experiment. At the moment the permeability test cell for grouted BHE's is under construction. First results will be available in summer 2009.

5. CONCLUSIONS

Quality control for ground source especially borehole systems has become an important issue because of the vast growing market in Germany. In 2008 the number of new installed BHE systems has reached about 20.000 with a tendency to a higher share of larger systems. Quality control has to cover the whole field from site investigation, design and simulation to construction and finally the operation phase. The project reported covers selected important parts. The results will also be considered in the new edition of German VDI 4640 Guidelines – Thermal Use of the Underground (2001).

While in the case of small systems, the design and planning can mostly be done based on assumptions and estimations, large systems require detailed geological and hydrogeological

underground assessment, site investigation and system simulation. Over the last few years the Thermal Response Test has been established in the market as a helpful instrument to gain reliable data for system design. Nevertheless this method has still a large potential for further development. Among others the development of improved evaluation models is important to facilitate the evaluation of the measurements. Typically in Germany the geology varies with depth significantly because of different geological layers. This affects also the thermal properties of the ground like thermal conductivity and heat capacity. From vertical temperature profiles measured in the BHE before and after a TRT additionally the influence of different layers can be analysed. For large borehole fields it is possible to derive from such information the optimal borehole length for the construction. Furthermore the influence of ground water on the Thermal Response Test is important and will be investigated in this project. The main goal of this research is to find an approach for separation of conduction and convection effects. This may also influence the simulation model used later for design.

Today several design tools for BHE system are available which describe the geology and the borehole field quite in detail. The major disadvantage of them is that the building itself has to be analysed with other tools before starting the design of the BHE system. A new development of the University of Applied Sciences Biberach closes this gap. The design tool GEO-SYST includes both the building demand and the ground source system. For a fast attempt but also for a full design this approach is extremely useful.

The increasing market created concerns at the water authorities regarding the sealing of boreholes. Although today borehole grouts are produced by professional companies on an industrial scale these materials may be damaged during regular operation especially by freezing and thawing cycles. Damaged means in this context that the coefficient of permeability increases during regular operation. In principle this can result in unintended connection of two aquifers or in case of leaking pipes to pollution of an aquifer by antifreeze and corrosion inhibitors of the heat transfer fluid. A test rig was designed to investigate this under controlled conditions in the laboratory. The relevant parameter is the coefficient of permeability of the whole system consisting of BHE pipes and grout. First results are expected in summer 2009.

6. ACKNOWLEDGMENT

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