Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

DATA ANALYSIS OF THE DEEP BOREHOLE HEAT EXCHANGER PLANT WEISSBAD (SWITZERLAND)

T. Kohl[1], M. Salton[1] & L. Rybach[1]
[1]Institute of Geophysics, ETH Hönggerberg, CH 8093 Zürich
E-mail: kohl@geo.phys.ethz.ch, Tel.: +41 1 633 3332, Fax: +41 1 633 1065

Key Words*:* heat flow, deep borehole heat exchanger, well casing, numerical modelling

ABSTRACT

The operation of the 1213 m deep borehole heat exchanger (BHE) plant Weissbad has been measured in over two year lasting measurement period. The temperature and performance data were reported at approximately one week intervals. It became evident from these measurements that the BHE output temperatures were significantly lower than expected. Understanding the reason for this discrepancy was the goal of the present study. By numerical simulation an axis-symmetrical model was developed which accurately represented the subsurface casing installations and the operational history. Sensitivity studies showed that different operation cycles which might not have been registered by the measurement intervals do not significantly change the model results. The initial simulations result in a rather constant offset of 1.8°C to the measured data. The produced temperature shows a strong sensitivity to the existence of a loose contact zone between the cementation and the casing. The measurements could be fitted perfectly by the assumption of a 1 cm thick layer between these two units with 75% porosity extending over 1/3 of the total depth range. Another reason for the low temperatures is the steel tube which hydraulically separates but thermally connects the upcoming from the downgoing flow path.

1 INTRODUCTION

The borehole heat exchanger (BHE) has found favour in several countries in recent years, mostly as a low-temperature heat source for heat pump (HP) based space heating systems. This reliable shallow heat source has become particularly popular in Switzerland, where at present over 20'000 such plants are in operation with borehole depths of 50 – 250 m (Rybach et al., 2000).

There exist also many deep boreholes, otherwise unused (failed "dry" holes drilled for the search of oil, gas, or even geothermal resources). These can lend themselves to development as BHE's and consequently a new type of geothermal direct use. The drilling costs have usually been written off; new investment for their re-use can be restricted therefore to eventual cleaning-out costs plus the completion of the well as a closed-circuit heat exchanger (Rybach and Hopkirk 1995).

The most popular type of construction used for shallow BHE's consists of single or double U-tubes backfilled into the borehole (Rybach and Sanner 1999). In deeper drillholes, the presence of a liner will imply that a coaxial construction, offering potentially better scope for thermal and hydraulic optimisation should be used. "Production" or heat delivery is then via a centred coaxial pipe and the return via the annulus.

The present study describes the performance over two consecutive years of operation of a 1.2 km deep borehole equipped in this manner to form a BHE in Weissbad (canton Appenzell Innerrhoden, 62 km east of Zurich). The performance characteristics are evaluated by numerical model simulations.

2 BHE PLANT WEISSBAD

2.1 Background

A drillhole of 1.6 km depth was deepened in 1993 with the aim to of finding a porous/fractured aquifer at depth. The directly adjacent spa and hotel complex of "Hof Weissbad" was envisaged as the heat consumer. The drillhole has encountered tight formations only and therefore it was decided to equip the well with a deep BHE. For this purpose the well was cemented up to 1213.3 m and a centralised steel pipe was inserted. Fig. 1 shows the casing schedule so completed.

The drillhole traverses Tertiary Molasse formations (Lower Sweetwater Molasse and Lower Marine Molasse), mainly tight sandstones and conglomerates. A temperature log run at near-equilibrium conditions in August 1993 shows a smooth temperature-depth curve with 45°C at bottom hole (1200 m).

Pure water is circulated in the deep BHE as heat carrier. The plant is equipped with two HELIOTHERM HP's. The circulation flow rate is 10.5 m^3h^{-1} (about 3 ls^{-1}). The original design expected to achieve a BHE delivery temperature of about 15°C in the long term.

2.2 Operational Data

A measurement campaign, accompanying the deep BHE plant operation, was initiated and financed by the Swiss Federal Office of Energy (BFE, Bern). The company Oekoplan AG acquired numerous data such as BHE outflow and return temperatures, and HP running times in the time span between 8 November 1996 and 7 November 1998. The data are compiled in two unpublished reports of Oekoplan AG to BFE. On the average the data are reported at one week intervals. The system operates at a seasonal performance factor of 3.42 and a coefficient of performance of 3.91.

It became evident from the measured data that the BHE output temperatures were significantly lower than expected: only 10.6°C on yearly average. The temperature varied between 14 and 9°C over the total period (see later Fig. 5). As expected the data show a minimum during the winter times and an increase after the heating season. An unexpected temperature peak occurred around March 1997 with a sudden increase of 4°C. This can be attributed to an erroneous measurement device or to a measurement occurring just after the begin of a fluid circulation (see Section 3.2). The reason for the lower-than-expected output temperatures should be clarified by the numerical model simulations described below in detail.

2.3 Numerical tool

For the simulation of the thermal behaviour of a BHE systems the finite element (FE) code FRACTure (Kohl & Hopkirk, 1995) was used. This program has already often demonstrated its capabilities for general purpose simulations in geothermal related fields. A special feature of this code is the combination of lower and higher dimensional elements. Thus, a 1-D element can be used for calculation of transport in tube-like structures which are surrounded by 2-D or 3-D matrix elements. Furthermore, the impact on the thermal transport of topography or hydraulic groundwater flow (forced or density driven convection) can be calculated in selected regions of the model domain. The simulation assumes the following thermal transport mechanisms: transient change of heat content, diffusion, advection and heat transfer. These may be written as follows (Kohl 1992):

$$\overline{rc_p} \times \frac{\P T}{\P t} = \nabla \times \left(\overline{l} \times \nabla T \right) - \left[rc_p \right]_f \times \mathbf{v} \times \nabla T + h \times {}^{A}\!/_{V} \times \Delta T \qquad (1)$$

with T temperature, t time, $\overline{rc_p}$, heat capacity of rock, $\overline{l}$ thermal conductivity of rock, **v** Darcy velocity, $[rc_P]_f$ heat capacity of fluid, h heat transfer coefficient, A cross-section of heat transfer, V volume.

The FE mesh generation is performed by the new interactive, semi-automated WinFra program. A link to common CAD programs is established via the implemented DXF-interface and allows the generation of technical or geological structures to be performed easily. This allows the different dimensionality associated with BHE simulation concerning the thickness of liners or casing ($<10^{-2}$m) and of geological units ($>10^2$m) to be achieved accurately. By defining individual load-time functions the transient evolution of selected system parameters or boundary conditions, such as flow in the BHE or surface temperature, can be controlled. By discretizing a measured history of the activity of the deep BHE plant Weissbad its operation schedule can be transferred exactly into the numerical calculation scheme.

3 NUMERICAL SIMULATION

3.1 Boundary Conditions and Geometry

The geometry and boundary conditions were chosen according to the goal of this study, which was to fit the measured output temperature of the deep BHE plant using the measured history of flow and temperature. Therefore, the measured return temperature of the heating system has been defined as input temperature (i.e. boundary condition) for the BHE system. A constant mean annual surface temperature of 9°C was taken; this causes only minor errors to the simulation since the annual temperature variations affect only the topmost ~15 m and therefore can be neglected for the total depth range of the BHE plant. At a depth of 1500 m the basal heat flow value of 75 mW m^{-2} was taken from the geothermal map of Switzerland (Medici & Rybach 1995). The geometry of the deep BHE plant Weissbad allows an assumption of axial symmetry around the centre of the system offering the advantage of performing 3-D simulations by 2-D calculations (Radius r, depth z). Due to the 1-D flow circulating in the tubes the model could make use here of lower dimensioned 1-D tube elements. They offer the advantage of calculating accurately thermal advection at high fluid flow rates. A mean mass flux during operation of $2.92\text{x}10^{-3}$ m^{3}s^{-1} has been defined, causing a variation of the fluid velocity due to changes in the diameter of the casing with $v_1(0<z<800\text{m})=$ -0.085 m s^{-1} and $v_2(800<z<1200\text{m})=$ -0.210 m s^{-1} along for the downward flow in the annulus and a constant value of $v_3(0<z<1200\text{m})=$ 0.999 m s^{-1} along for the upward flow in the central pipe. By defining appropriate load-time functions this mass flux could be activated, throttled or deactivated with time.

In addition to the 1-D elements for the representation of the BHE system the lateral extensions of the two tubings (central pipe and casing) had also to be also resolved to account for the heat transfer with the surrounding material. It can be established from Fig. 2 that the deep BHE's geometry could be represented accurately by a diameter of $7.6\text{x}10^{-2}$ m and a thickness of $7.0\text{x}10^{-3}$ m. The casing diameter was discretized with a diameter of $24\text{x}10^{-2}$ m and a thickness of $8.0\text{x}10^{-3}$ m. Inside both tubes identical lateral temperatures were assumed, thus neglecting effects of convection or non-laminar flow. By this formulation it could be ensured that the thermal transport in the 1-D elements along the tubings is dominated by forced advection with lateral heat transfer into the surrounding material. The specific heat transfer coefficient, h, is calculated by

$$h = \frac{l_f \times Nu}{D} \qquad (2)$$

with Nu the dimensionless Nusselt number (e.g. see Somerton 1992), l_f the fluid thermal conductivity and D the diameter of the tubing. The total model assumed four individual material sets: the BHE fluid, the casings of the two tubings, the backfilling material (cement) and the surrounding rock. The properties used are given in Table 1.

3.2 Sensitivity of Operation Conditions

The measured operation data of the Weissbad plant were registered at 4 - 14 days increments (Salton 1999). Each period comprised several operation and recovery cycles. The length and frequency of individual cycles could not be established from the field reports but only the total number of operation and recovery hours in each measurement interval. Since this uncertainty can have a key impact on the overall system behaviour it was necessary to identify the impact of individual cycles with different lengths. In the calculation scheme a variation of the length of one cycle can be performed by changing the load-time function parameters. An example of such investigation is illustrated in Fig. 3 with two time steps during recovery (flux = 0) and one time step each preceding and succeeding the recovery phase. The calculations were performed finally with time steps of 3 h after each activation. Two different assumptions were investigated for a basic model extending over a 20 days time span with a total of 6 days recovery, a typical mass flux of $2.92\text{x}10^{-3}$ m^{3}s^{-1} and a constant inflow temperature of 10°C. The length of these recovery phases was varied between 6 days (i.e. 1 recovery phase between day 8 and 14) and 2 days (i.e. 3 recovery phases at days 6/7, 10/11 and 14/15). This model sensitivity study showed that the final BHE outlet temperature for these models varied only marginally. The maximum temperature produced was 15.343°C for the model assuming one recovery phase and 15.334°C for the 3 recovery phases. These results indicate therewith that the BHE performance cannot be improved by a variation of the cycle interval.

Fig. 4 illustrates a typical example of the transient BHE behaviour for the case of 3 recovery phases: Initially, after the start of operation, the temperature increases up to 30°C due to the warm standing water column but reduces after one day to

16°C. After 6 days the first recovery phase starts and the temperature immediately drops to nearly annual surface temperature. It may be noted that this phase is not interesting for performance considerations since the total system including HP does not operate. After another two days, operation starts again and the temperature peak becomes visible again. This time, however, due to the shorter standing time of the fluid column in the tubings, the peak reaches only 26°C. Again, this peak is also not significant for performance considerations since it drops fast to lower values when the total column has been circulated. It can be also recognised in Fig. 4 that the shape of these temperature curves does not change after the second or third recovery phase. These analyses have demonstrated that different production / recovery cycles do not significantly change the performance of the Weissbad plant within one measurement interval. The subsequent simulations were performed under the assumption of one recovery phase of the reported length between an individual measurement interval.

3.3 Simulation results

The goal of this simulation study was to fit the measured BHE outlet temperature history by a numerical model assuming realistic parameter sets. First simulations were performed for the period between November 8, 1996 and November 7, 1997. With the exception of a temperature peak of 16°C occurring in March 1997 (see Fig. 5) the data show the expected trend with a temperature minimum at the end of the heating season and a temperature maximum before the start of the heating season. Since the return outlet temperature follows this trend a similar temperature curve at an approximately 5°C lower level has been used as input function for the BHE system.

Fig. 5 shows a comparison between measurements and modelled data. The modelled data are generally 1.8°C lower than the measurements. The difference persists even after more than one year. However, sharp measured temperature peaks (e.g. 27 Nov. 1996 or 17. Dec. 1996) are smoothed out by the simulations. The reason for these temperature variations are most probably short time spans after the begin of an operation cycle. It was noted earlier, that the correct onset of each cycle remains unknown and could thus not be considered. This fact represents a major problem for the total measurement period since the input temperature generally tends to become too high when recorded shortly after the onset of operation. However, this cannot explain the total difference between measured and modelled data. Another reason is the assumed homogeneity of the material sets which prevails only under ideal conditions. In reality, some of the selected parameters may strongly differ.

In following model runs it has been attempted to obtain better fits by reducing the values of basal heat flow, constant annual surface temperature and thermal conductivity of the rock. These supplementary runs have demonstrated that

- a reduction of the basal heat flow value within a realistic range has no significance to the output temperature
- a reduction of the annual mean surface temperature does not significantly reduce the BHE output temperature
- the most dramatic temperature effects can be achieved by a variation of the thermal conductivity of the medium surrounding the BHE. Reducing its thermal conductivity down to 2.0 W m^{-1} K^{-1} yields a reduction of the BHE output temperature of 0.6°C.

These results indicate that possibly the contact between casing and rock may be of major importance. Therefore, a slightly different model has been developed including a 1 cm thick contact zone between the casing and the unperturbed rock. This contact zone should represent gaps or loose contact in cementation and is assumed to have a low thermal conductivity. In reality bad contact zones are arbitrarily distributed between the rock and the casing - in our model we assume such a zone to exist in a continuous depth range between 800 and 1200 m. Fig. 6 demonstrates the sensitivity of a variable thermal conductivity to the mean difference between model and measured data. At a thermal conductivity, λ, of 0.10 W m^{-1} K^{-1} the modelled temperatures would be even smaller than the measured data. Clearly, at λ= 2.50 W m^{-1} K^{-1} the same situation like in the initial model would result, demonstrated by Fig. 5. Applying however a value of λ = 0.15 W m^{-1} K^{-1} both curves coincide. This agreement is remarkable and can be seen in Fig. 7. Even the extension of the data set to November 8, 1998 results in a nearly perfect agreement.

The absolute thermal conductivity value of such a contact zone depends on its thickness, Δx. Our investigation can only indicate an equivalent thermal resistance, $\Delta x/\lambda$, of 0.067 m^2 K W^{-1} over the depth range 800-1200 m. Assuming the thermal conductivity of the contact zone being the geometrical mean of the two portions, fluid (λ=0.6 W m^{-1} K^{-1}) and concrete (λ= 2.0 W m^{-1} K^{-1}), its porosity can be estimated for different Δx: For Δx varying between 4 and 7 cm the porosity decreases from 100% to 68%. It may be noted that these values decrease in the presence of air (λ=0.025 W m^{-1} K^{-1}) instead of water. These estimations show that there are potentially large void spaces behind the casing.

4 CONCLUSIONS

The first two year operation of the deep BHE plant Weissbad has shown unexpected low temperature return values. Assuming ideal conditions of the subsurface installation the numerical simulation of the available data indicates a mean temperature difference to the data of 1.8°C. There are several reasons that can explain this difference:

The temperature reading is not necessarily a representative BHE input temperature for the temperature history of the total interval since the circulation fluid is strongly heated at the begin of each operation cycle.

During installation of the casing an optimum contact to the surrounding medium hasn't either been achieved nor initially intended. Under the assumption of a 1 cm thick loose contact zone extending over 1/3 of the total borehole an equivalent thermal conductivity of 0.15 W m^{-1} K^{-1} is required to match the data. This would correspond to a porosity of ~75%, however, contact zones of different sizes will change this estimation. It may be noted that such loose contact is not unlikely to occur in subsurface due to thermal stresses developing around the Weissbad borehole. The stresses created by an imposed temperature difference of maximum 35°C (compare the BHT of 45°C to the mean BHE output temperature of 10°C) are able to deform the surrounding rock and to create void spaces close to the borehole. Similar observations are also the subject of investigations at other institutions (M. Allan, Brookhaven Nat. Lab., personal communication). Another reason for the existence of voids is due to the drilling at greater depth: the increasing magnitudes of the stress field create borehole breakouts which remain present after the installation of the casing.

The total system performance could be improved by using different types of central pipes. In this case, a steel casing was used, which potentially enables high heat transfer from the downgoing to the upcoming fluid. By isolating especially the upper parts of this installation the energy output of the system can be improved. This is, however, a subject of further investigations.

ACKNOWLEDGEMENTS

Sincere thanks are due to several persons who supplied valuable information: Mr. St. Berli (Gossau), Dr. W. Eugster (Zurich), Mr. A. Rissi (Zurich).

REFERENCES

Kohl T., (1992), Modellsimulation gekoppelter Vorgänge beim Wärmeentzug aus heissem Tiefengestein, Ph.D. Thesis ETH Zürich, No 9802, Switzerland

Kohl T. and Hopkirk, R.J., (1995), "FRACTure" a simulation code for forced fluid flow and transport in fractured porous rock, *Geothermics*, Vol.24(3), pp 345-359

Medici & Rybach (1995): Geothermal map of Switzerland (Heat flow density); Matériaux pour la Géologie de la Suisse, Physique Nr. 30

Rybach, L. and Hopkirk; R. (1995): Shallow and deep borehole heat exchangers – Achievements and prospects. In: Proc. World Geothermal Congress 199, vol. 3, p. 2133-2138, Int. Geoth. Assoc. Inc., Auckland/NZ

Rybach, L. and Sanner, B. (1999): Ground-source heat pump systems – the European experience. In: Proc. International Geothermal Days – Oregon 1999, Vol. 1 p.159-170. Geo-Heat Center, Oregon Inst. of Technology, Klamath Falls/USA

Rybach L., Gohran H., (1995): Swiss Geothermal Energy Update 1990-1995. In: Proc. World Geothermal Congress 95, Vol. 1, Florence (I), 329-337.

Salton, M. (1999): Untersuchungen zum Verhalten von Erdwärmesonden. Unpublished diploma thesis, ETH Zurich, 90 p.

Somerton W.H. (1992): Thermal properties and temperature related behavior of rock/fluid systems, Elsevier

TABLE

Table 1: Thermal parameters of the BHE plant Weissbad

	Thermal conductivity [W m^{-1} K^{-1}]	specific heat capacity [J m^{-3} K^{-1}]
Fluid	0.6	4.2×10^6
Casing / Central Pipe	45.0	3.5×10^6
Cement	3.0	2.0×10^6
Rock	2.5	2.5×10^6

FIGURE

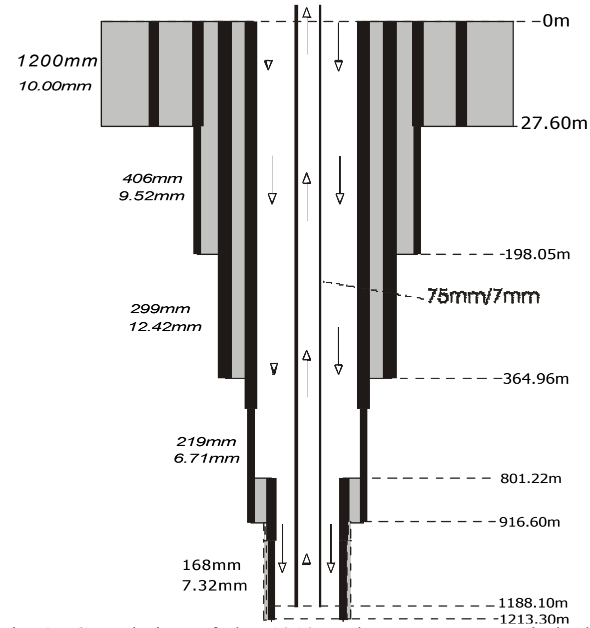

Fig. 1: Completion of the 1213 m deep *BHE in* Weissbad . Depth in m is given on right margin, outer casing diameter and thickness on the left margin. Black: casing, grey: cementation between pipes.

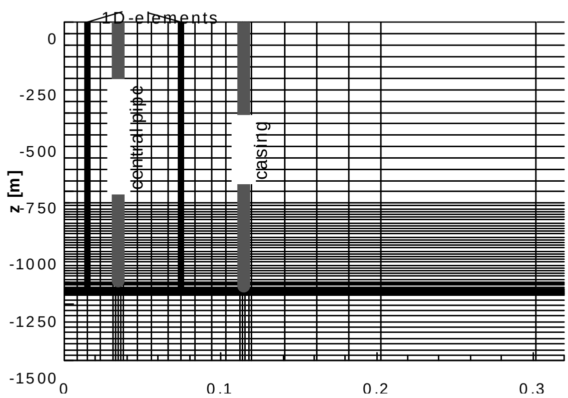

Fig. 2: Discretization in the near field of the Weissbad model. The horizontal "black line" at a depth of ~1200 m indicates a strongly refined vertical discretization. Note, the axes are scaled independently.

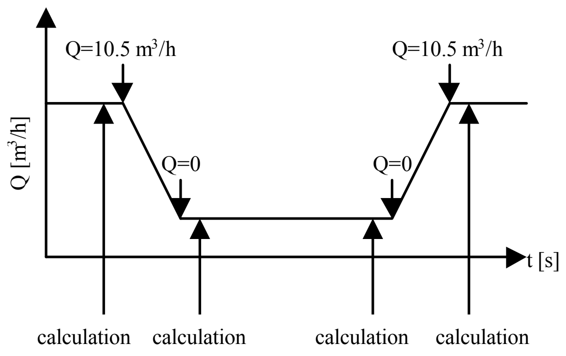

Fig. 3: Illustration of load-time function.

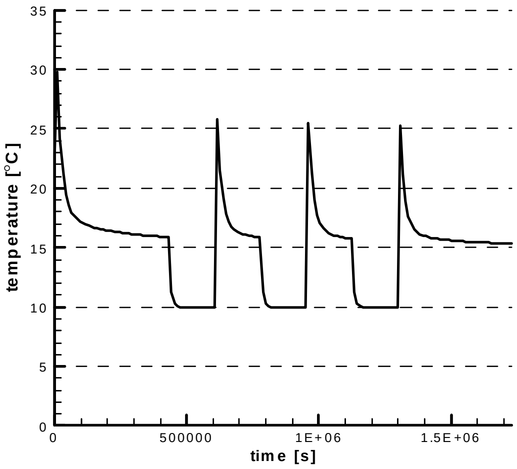

Fig. 4: Transient behaviour of produced temperature during operation and recovery phases.

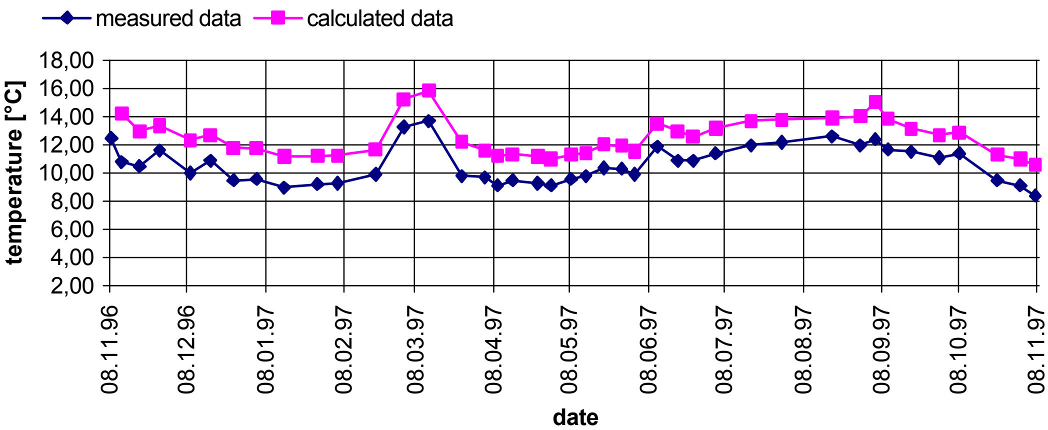

Fig. 5: Comparison of measurements to initial model response. The simulated data are approximately 2°C higher than the measured data.

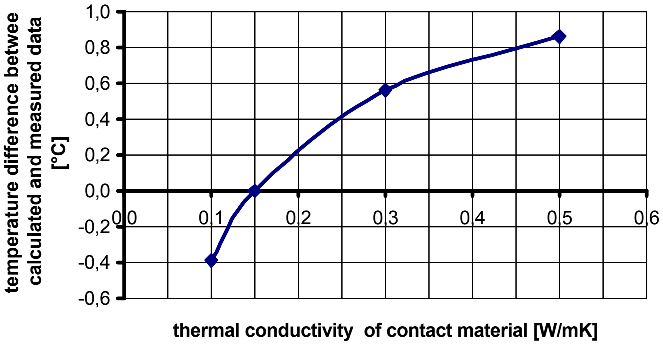

Fig. 6: Sensitivity of contact zone.

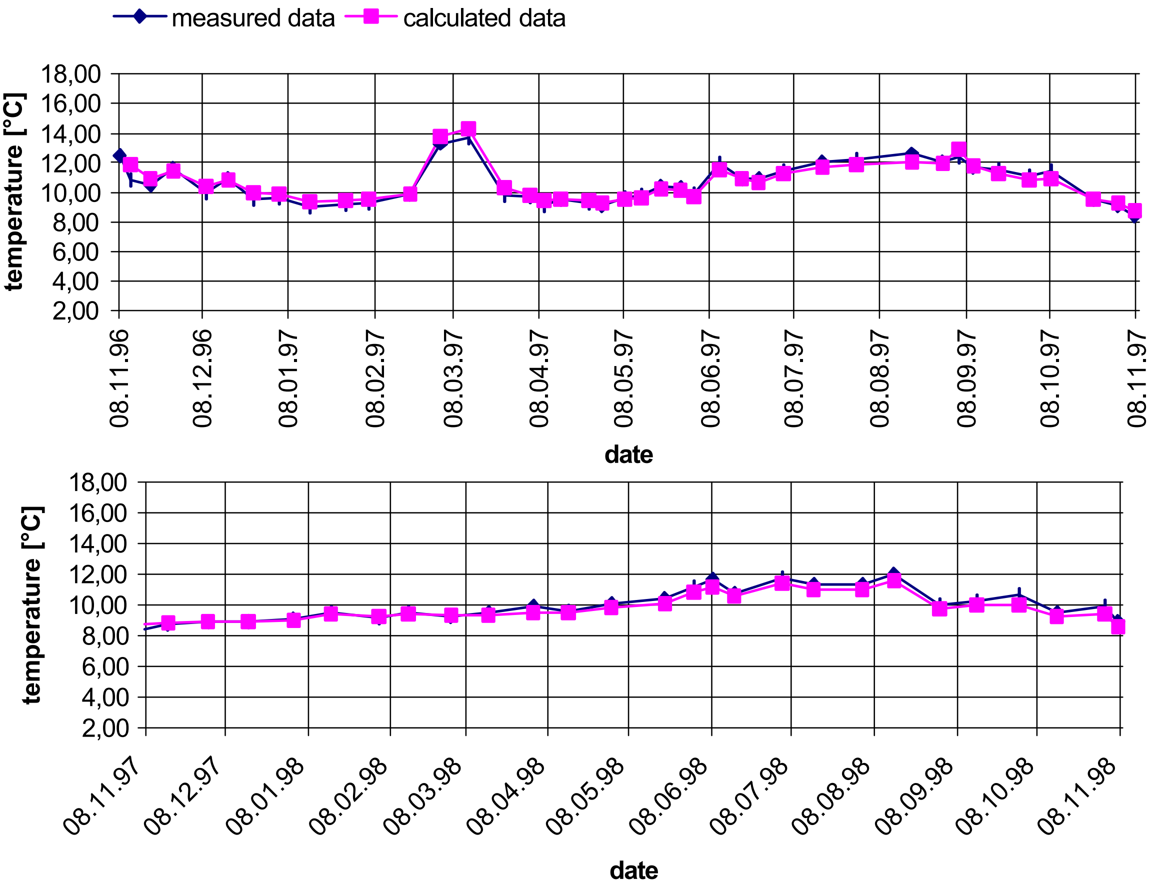

Fig. 7: Comparison of measurements to modified model response over the period Nov. 1996 - Nov. 1998. The simulated temperature at the outlet of the BHE system matches well the measured data.