GeoStar – a Scalable Borehole Heat Exchanger System

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ABSTRACT

The implementation of low-temperature district heating systems with central heat pump stations in large and growing urban infrastructures is a difficult investment. Generally the development of new city quarters lasts several – often more than ten - years. Centralized heating stations with ground coupled heat exchangers may serve the district heating system; this is normally constructed together with road works and with the subsurface infrastructure like waste-/freshwater pipes and electricity / communication cables. However, investors want to pay the expensive bills for the last necessary boreholes not earlier as the last buildings are constructed and the last consumer is connected to the grid. Therefore a scalable heat pump (HP) system in combination with a growing borehole heat exchanger (BHE) system over time is required. While central HP-stations may easily be enlarged by just adding unit by unit on request, new boreholes and ditches are complicated to be constructed and connected in an already built environment without re-opening of roads, pavements, disturbance of traffic etc.. When additional consumers are added to the grid it is most likely desirable to drill more boreholes just from one existing spot. Such growing “hot-spots” are already connected to the heating station. This concept requires a new design of BHE fields leading to deviated wellbores that are drilled from one site in a radial arrangement – a GeoStar. This design is also applicable for heating and cooling of already existing large building complexes in constricted urban areas with limited space. A first GeoStar prototype has been realized in a research project in Bochum, Germany. The aim was a) to develop the drilling technology for deviated and stable boreholes in larger depths, b) to install a set of up to 20 BHE (200 – 500 m) in a star-shaped manner for heating and cooling with a set of 4*35kW HP and c) to understand the performance and possible thermal interferences of BHE with different cementations. As an outcome of the R&D program a first reference unit was taken into operation at the new GZB campus. In total 17 inclined BHE were installed plus 3 monitoring wells; all of them running from a central spot to depths of 200 m in angles of up to 15°. All wells are completely equipped with optical fibers for distributed in-situ temperature sensing and for investigations on the thermal and mechanical influences on the performance of the fibers plus on the thermal rock and cement properties during operation. From beginning of the construction an extensive and unique scientific measuring program was carried out. It involved logging and analysis of drilling parameters, borehole deviations and rock structure (borehole geophysics), thermal conductivity (Enhanced Geothermal Response Tests) and temperature (Fiber Optic Measurement Techniques). Based on the measured data, a three-dimensional geological model was created which is also used for numerical heat transfer simulations. Currently a long-term monitoring is being carried out during the operation of the BHE-system. That allows a calibration and validation of the simulation model and will give an insight to the energetic performance of the whole BHE-DH-HP system at GZB.

1. INTRODUCTION

Renewable heat generation with geothermal energy is becoming increasingly popular for private house building as well as for office and administrative building. The geothermal energy source is typically exploited by shallow geothermal probes using ground coupled heat exchangers up to depths of 100 m. If larger plan areas are thermotechnically exploited, the costs for drilling, pipes, and moving the equipment from borehole to borehole increase by orders of magnitude. This way, large borehole heat exchanger (BHE) fields with a dense network of pipes along with trench and shoring work are required. Additionally, the amount of space necessary for the technical equipment is comparatively large. As a consequence, this technology is often not applicable for building redevelopment such as modernization of heating systems.

Centralized geothermal heating stations with larger drilling depths between 200 m and 800 m can be realized with cost-efficient mobile drilling facilities and reduce the demand of space significantly. The main criteria for economically operating geothermal systems are

- the price development for fossil fuels,
- the geological quality of the location, and
- technological advancements, in particular with respect to drilling process technologies and the construction of underground heat exchangers.

Today the underground components of a geothermal system account for roughly 70 % of the total costs. Technological improvements related to the drilling process are essential to lower these costs. The initial focus should be set on the development of faster, more efficient drilling methods for intermediate depth levels between 200 m and 1000 m.

In addition to drilling technologies the development of centralized heating stations for intermediate and great depth levels for the heat supply of large plan areas is in its infancy. Despite their indisputable ecological advantages these systems could not yet be successfully introduced to the energy market due to the high initial investments for heat contracting of central geothermal heating systems. Large supply infrastructures are usually developed for periods of 10 years or more (Winkler et al. 2007, Hoefker et al. 2007). High initial investments for the centralized heat supply of large plan areas, for example by a deep BHE, prove uneconomical for supply companies considering the long time of exploitation. For that reason new concepts for heating stations have to be developed providing the possibility to successively enhance the capacity through a stepwise upgrade of the heat exchanger system over long periods of time. At the same time, existing infrastructures of the supply area (streets, pipes, etc.) have to remain unaffected, because additional frequent engineering and laying works would increase the costs and impairment of citizens dramatically.

The problems identified above inspired the GeoStar research project funded by the German Federal Ministry of Education and Research (BMBF) within the framework of FHprofUnt. The innovative character and aim of the project is the development of a centralized heat supply concept for large plan areas to temporally extend the initial investments for large geothermal systems according to the demands. The integrated R&D concept is based on

- innovative (vertical) drilling technologies for intermediate depth levels providing the basis for
- a new design of heating stations for large and centralized geothermal systems, which can be enhanced in capacity and with time, and their dimensioning including
- the required building materials and techniques for underground components of the geothermal system.

The scientific and technical objective of the research project described in the following was to develop a prototype of a centralized geothermal heat exchanger with a cooling capacity between 200 to 350 kW. The preceding BMBF-funded projects of the GZB related to improved vertical drilling technologies provided a number of technological prerequisites, which had to be further developed with respect to their application for the required deviated drilling. Starting at a common source point, wellbores in numerous deviated directions and drilling angles host BHE at intermediate depth levels (L = 200 – 400 m) in a star-shaped array. This “GeoStar” allows for successively increasing the number of wells with progressive development of the plan area and its heat demand. Coming from the hotspot, additional BHE strings can be placed for new construction stages as required without affecting the infrastructure of the developing area.

2. GEOSTAR PROTOTYPE AT THE INTERNATIONAL GEOTHERMAL CENTRE (GZB)

The Geostar prototype was originally planned to be installed and further developed on the 25 ha large building area No. 48 Schultenkamp / Dorfheide in Bottrop (northern Ruhr area), where 700 housing units are currently being built in several construction stages (Winkler et al. 2007, Hoefker et al. 2007). However, the model site had to be given up, because the project developer changed the energy supply concept to a decentralized individual supply system. The building project for the International Geothermal Centre (GZB) on campus at Bochum University of Applied Sciences served as an alternative location for the GeoStar, for which the available space was severely limited due to former mining activities and future research activities on drilling technologies. The star-shaped design of the GeoStar with deviated wellbores was a perfect utilization of the remaining area and is able to provide a monovalent geothermal heat supply.

2.1 Description of the building project

The new building was financially supported by the Ministry of Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of the German State of North Rhine-Westphalia (MKULNV NRW) within the scope of the project “GeoTechnikum”. The building site is located in the south-east of Bochum University of Applied Sciences and covers the following plan areas and buildings used for research, development, education and training at GZB (cf. Figure 1):

- a two story institute building (first floor: laboratories of geotechnologies, conference rooms; second floor: offices),
- a machine hall for large equipment with adjacent drilling site / in-situ-testing field for large-scale experiments under realistic conditions (= GeoTechnikum),
- the Energetikum, which serves as energy station, for education and training as well as for research

and development in the area of heat pump technologies incl. a heat pump test site and

- a 10.000 sqm in-situ Laboratory "Future Energy" for reservoir, drilling and geophysical experiments under real case conditions; the in-situ Lab is equipped with a seismic and hydrologic observatory and is directly connected to the Energetikum via a pipeline system for thermal waters. Two drill cellars provide access to the deep geothermal reservoir which will be developed in the next project phase together with the setup of a binary research power plant.

Figure 1: New buildings of the International Geothermal Centre (GZB).

2.2 Energy supply concept

Heating and cooling of the new GZB buildings will be performed monovalently with a BHE-coupled heat pump station. The heating load was previously determined to be 140 kW with an annual heat demand of 252 MWh and the cooling load was estimated to 85 kW with an annual cooling demand of 51 MWh. Four electrical brine-water heat pumps (Type: GEO 37) by Rehau with a total heat load of 4 x 34.8 kW (B0/W35) are used for heating and cooling of the buildings.

2.3 Geological and hydrogeological background incl. mining history

Up to a depth of about 1000 m the area of Bochum-Querenburg belongs to Westfal A (Bochum and Witten Formation) and Namur C (Sprockhoevel Formation, cf. Figure 2) of the coal bearing Upper Carboniferous. The geology is characterized by interlayered mudstones, siltstones and sandstones forming coarse to intermediate, partly conglomeratic minor constituents. At irregular intervals interlayered coal seams with variable thicknesses form approximately 5 % of this sequence decreasing with depth. The groundwater horizon exhibits low hydraulic conductivities of 10 - 9 m/s. The closer plan area is located in a local SW-NE-oriented syncline. On each flank the geological formations attain a dipping angle of 70° to south-east and to north-west, respectively. The syncline structure was mined up to a depth of 70 m. The area affected by former coal mining represents a large portion of the building area (cf. red area in Figure 3).

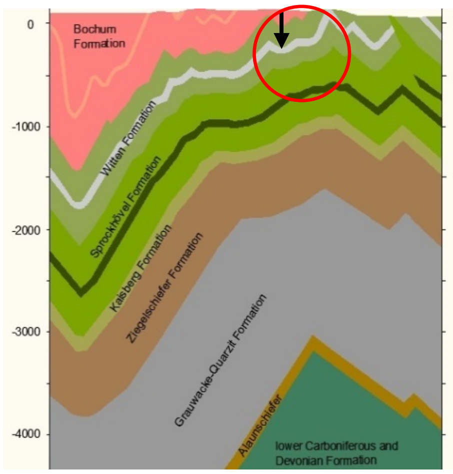

Figure 2: Geological profile

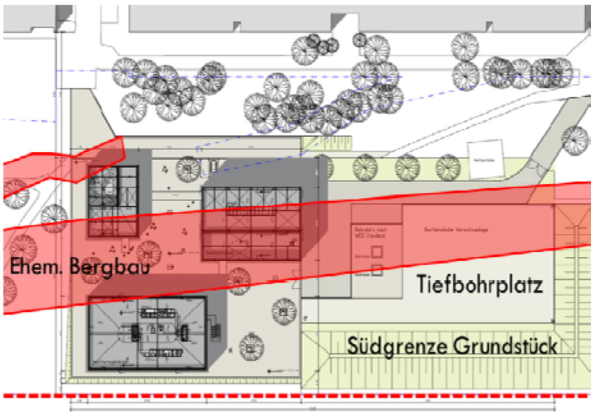

Figure 3: Location of former coal mining

2.4 Geometrical arrangement of GeoStar

During summer the BHE field of the GeoStar is supposed to be used as heat sink. Due to the significant amount of cooling load the exploitation depth levels for the BHE had to be limited to 200 m. Greater depth levels exhibit temperatures that are not efficient for cooling. In particular, direct cooling with shallow geothermal systems is impeded. Because of the ownership structure, the intended use of the building area and the former mining, only one appropriate location for the BHE field of the GeoStar in the north-west of the building area was identified (cf. Figure 4):

1. The central area was discarded due to potential drilling risks related to open cavities up to depths of 70 m.
2. The southern area was ineligible because of proprietary rights, since the deviated wellbores in the deeper underground would have left the area of the campus.
3. The eastern area competed with future plans for drilling activities.

Figure 4: Location and geometrical arrangement of the GeoStar array at the GZB

Due to the above restrictions some constraints related to the dipping angle of the wellbores had to be considered for the remaining drilling area. Dipping angles of 10 to 15° were not to be exceeded. In particular, a safety zone of 10 m distance to the unsecured old mining of the northern area had to be ensured (cf. Figure 5).

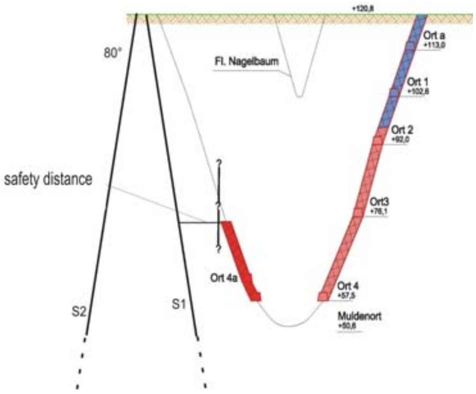

Figure 5: Safety zone to the unsecured old mining

Based on the energy demand (heating and cooling load) provided by the TGA-planning the geothermal supply of the new GeoTechnikum building a GeoStar BHE field consisting of 20 probes with depths of 200 m each and a total length of 4000 m was set up. Predimensioning considered a safety factor of > 10 % for potential imponderabilia and uncertainties during the construction work. The software Earth Energy Designer (EED 3.16) was used to calculate the number, distances and lengths of the BHE by converting the star-shaped array with deviated BHE to an equivalent rectangular configuration with vertical BHE. The probe distance was chosen to be 6.8 m corresponding to the average target distance between two adjacent BHE with a dipping angle of 10° in a star-shaped BHE array. For a viable angle of 15° the required distance is already 9.3 m.

2.5 Execution of the drilling program and installation of GeoStar

All drillings were performed with the university's own drill rig and personnel. The automotive track drill unit BO.REX (Bochum Research and Exploration Drilling Rig), a Huette HBR 207 GT (cf. Figure 7) with a total weight of 32 t and a retraction force of 40 t (+20 t reserve), allows for drilling up to depths of minimum 1000 m. The hydraulic down-the-hole-hammer drilling method was further developed for the deviated drilling and the installation of BHE and could successfully be applied despite of the rather unfavorable local geology (Wittig et al. 2012). The hydraulic DTH fluid hammer 6'' by the Swedish company Wassara (cf. Figure 6) was used in conjunction with a high pressure pump by Kamat company with a working pressure of maximum 210 bars and a nominal flow rate of 600 l/min. In contrast to pneumatic systems the hydraulic system is able to drill to greater depths without any increase in the consumption of water or diesel fuel as shown by the evaluation of operational data. However, the generally extensive consumption of supply water counteracts the total cost-effectiveness to some extent. Circulating the drilling fluid (water circulation with filtered fluid) would increase the economic efficiency of the hydraulic drilling technology significantly.

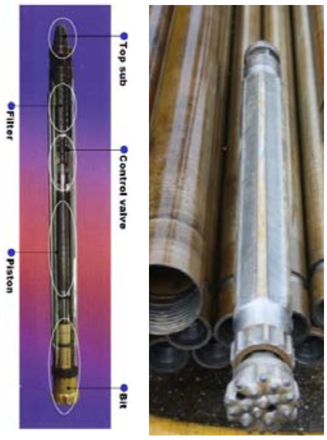

Figure 6: Setup of DTH Hammer and drill rods and DTH percussion hammer 6" by co. Wassara

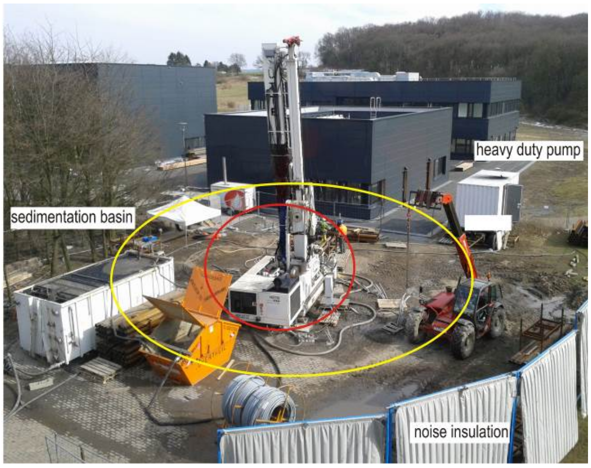

Figure 7: Drilling site and drilling operations with the GZB-drilling rig BO.REX

Due to the size of the drilling rig and the required rod handling while drilling it was not possible to start drilling from a common source point. Considering the local constraints the wellbores were drilled at regular intervals along a width of 10 m at the surface to realize the star-shaped configuration of the array. Figure 7 shows the drilling site at the International Geothermal Centre (GZB) with drilling rig, sedimentation basin, heavy duty triplex plunger pump and noise insulation. The red circle (cf. Figure 7) indicates the 6 m wide inner working area of the BO.REX drilling rig. Additionally, 5 m are required for rod handling and for exchanging the rod carriers (yellow circle).

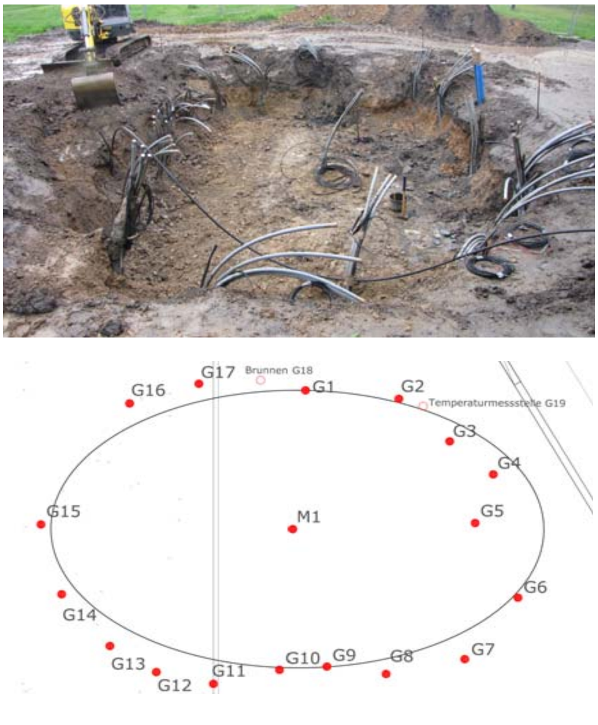

Figure 8: Building the BHE field of the GeoStar before connection to brine distributer

Figure 9: Installation of a BHE with coiler, placed PE-Xa (DN 40 x 3.7 mm)-probe with spacer

In total 17 BHE were installed on a 6 x 10 m elliptic area in a star-shaped manner with dipping angles of 10° to 13° up to depths of 190 to 200 m (cf. Figure 8). The total effective probe length is 3359 m. Prefabricated RAUGEO double-u probes made of PE-Xa with DIN 40 x 3.7 mm (cf. Figure 9, Figure 10) and factory-made probe feet were provided by Rehau company. Tubes made of PE-Xa exhibit significantly higher resistances to notching and crack growth and can sustain a larger range of temperatures (– 40°C to 95°C) compared to tubes made of PE 100. The BHE were installed in the water-filled wellbores using a coiler (cf. Figure 9, Figure 10) and installation weights. Probes were connected to a central distributer with a connecting pipe made of PE-Xa 50 x 4.6.

Figure 10: Installation of a BHE with coiler, placed PE-Xa (DN 40 x 3.7 mm)-probe with spacer

Figure 11: General view of the geothermal energy supply

3. SCIENTIFIC MEASURING PROGRAM

Because the university itself was responsible for planning, execution and utilization of the GeoStar, a unique scientific supporting program could be performed including the site investigation and the technical monitoring of the drilling activities. Data from the drilling process were continuously recorded and analyzed. This way the deviated drilling technology with probe handling could be optimized and the (economic) efficiency could be controlled while operating. Additionally, deviation and gamma logs were recorded for all wellbores for open holes as well as within the BHE (DMT mini logger). Well after grouting the undisturbed ground temperature was measured within the BHE using the wireless sensor NIMO-T (Non-wired Immersible Measuring Object for Temperature) by the Swiss company Geowatt AG. For future thermal monitoring all BHE were equipped with optical fiber cables. Thermal Response tests and / or Enhanced Geothermal Response Tests were performed for three BHE. These data in conjunction with the geological information were used to build a numerical geothermal 3D model of the subsurface to simulate the long-term thermal response of the BHE field as a function of abstraction capacity and time of operation.

3.1 Results of deviation logs

Deviation logs were recorded to document the directional stability of the deviated wellbores continuously while drilling to prevent negative thermal interactions due to insufficient distances. The updated results were used to identify the starting point and dipping angle of the next drilling. A general trend of the wellbores to drift towards NW (perpendicular to the dominant striking of the Upper Carboniferous formations) could be identified (cf. Figure 12, Figure 13). The deviation of wells dipping to NW increases significantly (> 20°), while that of wells dipping to SE decrease to 0°. The results show that the drift towards NW caused the distances between individual BHE to become significantly larger than the target distances. The mean probe distance for all 17 BHE amounts to 9,05 m. Using the program EED it was shown that the BHE field is sufficiently dimensioned to supply the energy demand for the new building (cf. chapter 2.2).

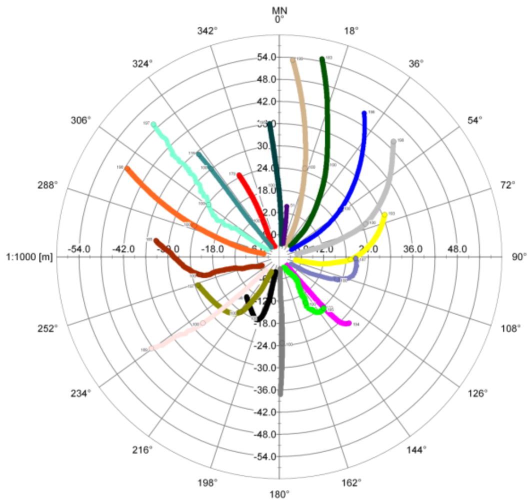

Figure 12: Bulls-eye presentation of deviation logs of the GeoStar BHE field

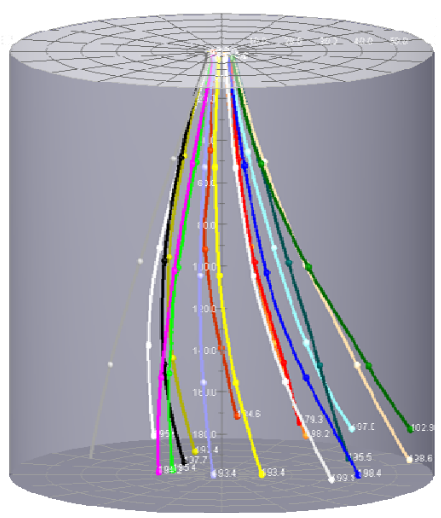

Figure 13: 3-D-presentation of deviation logs of the GeoStar BHE field with Well-Cad (viewing direction East to West)

3.2 Enhanced Geothermal Response Test

The Enhanced Geothermal Response Test (EGRT) was further developed based on the geothermal response test (Gehlin et al. 2002). The main improvement is that the thermal parameters, thermal conductivity and borehole resistance, are determined accurately as a function of depth instead of providing a sum parameter (Heske et al. 2011). For the applied EGRT (Figure 14) a hybrid cable, which consists of an integrated heating and measuring cable, is inserted into the borehole along with the geothermal probe. By applying a heating voltage to the copper electric conductor in the hybrid cable, a defined heating power is placed to the underground for about 120 hours.

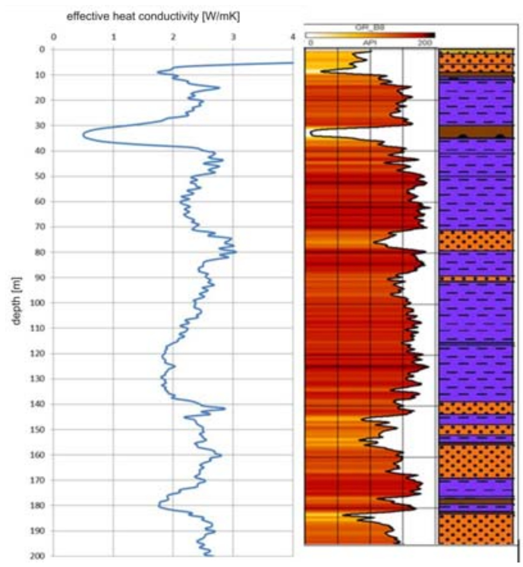

Figure 14: Measurement results of the EGRT showing the thermal conductivity in comparison to the GR-measurement and rock characterization

Simultaneously, the generated temperature change along the LWL-measuring cable is recorded using fiber-optical measuring technique. Based on the line or cylindrical source theory, the distribution of the thermal material parameters can be determined as a function of depth (e.g. per meter) along the LWL-cable. The penetration depth of the heat front generated by the application of the heating voltage is a function of heating time. By evaluating the temperature curves of short heating intervals the thermal parameters of the backfill of boreholes along the measurement path can be determined. Since the hybrid cable remains installed in the underground permanently, the Enhanced Geothermal Response Test can be repeated at any time. The subsurface temperature distribution and the thermal material parameters can also be determined with modified boundary conditions. The installation of the measuring equipment is mainly limited to the correct placement of the measurement and heating cable in the ground. During insertion the cable is attached to the probe at the probe foot and drained into the borehole together with the BHE. The heating cable is connected to a power source with a constant voltage and the fiber optic cables are connected to the DTS device (Distributed Temperature Sensing). Figure 14 shows the thermal conductivity compared to the gamma log and the layer profile for a selected BHE (G7) as measured by EGRT. In this case, a very good correlation can be observed.

Thermal conductivities up to depths of 200 m range between 0.5 W/m/K and max. 3.01 W/(K·m). The minimum of 0.5 W/(K·m) is located at a depth of 30-35 m for a poorly heat conducting coal seam, and the maximum of 3.01 W/(K·m) is observed at 70 - 80 m depth for a sandstone bench. The average thermal conductivity across the entire probe length is 2.55 W/(K·m). Comparative GRT measurements show an average effective thermal conductivity of 2.53 W/(K·m).

3.3 Underground and temperature model

Based on borehole geophysical measurement data, a very detailed geological subsurface model of the GeoStar probe field could be created using the PETREL-Software by Schlumberger. In particular, dipping and striking of the layer sequences could precisely be determined. No lithological differentiation between clay and sandstones was possible due to the small scale of interchanging layers and their weak differences in gamma intensities. However, coal seams could be clearly identified lithologically and in GR-intensities.

Figure 15 shows the courses of the layers in a profile through the center of the GeoStar. The modeled layer courses in the borehole agree very well with the known sections of the geological map and the mine map of the coal mining areas. The general local dipping trend from NW towards SE is clearly visible. Looking at the courses in the borehole it becomes obvious that drilling aligns vertically to the slice orientation, which explains the distractions described in 3.1.

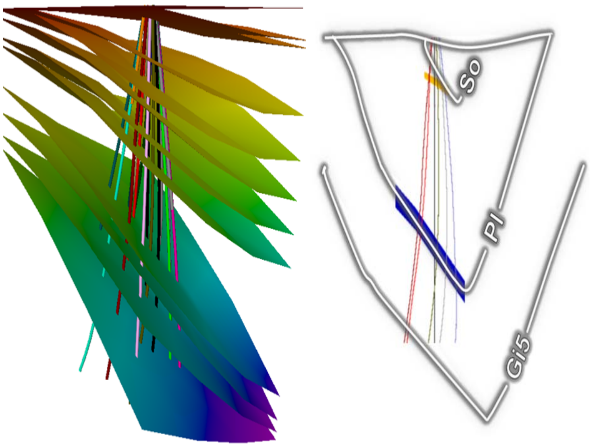

Figure 15: Subsurface model (looking SW-NE) in the area of the probe field of the GeoStar with course and lithological boundary layers and correlation with stratification (leading seam) of the geological map

Owing to the complete temperature profile along the sunken BHE a detailed temperature model could be created. The spatial distributions of the isothermal lines in steps of 0.5°C are shown in Figure 16 and demonstrate a temperature gradient with decreasing temperatures from northwest to southeast in the GeoStar-Field. Here, the undisturbed ground temperatures in the northwest are significantly higher than in the southeast at equivalent depth. It can be concluded that the temperature distribution is strongly affected by the local geology and less dependent on the vertical temperature gradient. Direction and deviation of the isotherms correlate well with the geological horizons. It is assumed that this temperature bedding along the geological horizons is particularly caused by the position of the coal seams forming sheet-like heat insulators. As a consequence, at least a portion of the geothermal heat flux from the Earth’s interior occurs along the geological striking direction of highly thermally conductive clay and sandstone layers rather than vertically.

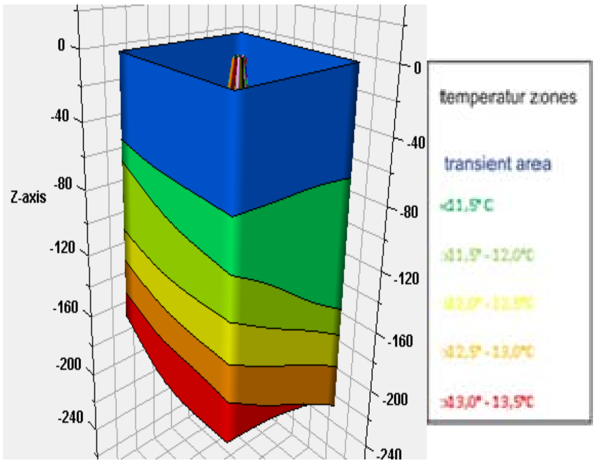

Figure 16: Temperature distribution in the subsurface

3.4 Numerical heat transport simulation

One of the main objectives of this research project was to demonstrate the performance of a GeoStar probe arrangement via corresponding numerical heat transport simulations (Cui et al. 2006). Using common software tools available on the market no direct realistic simulation of inclined BHE arrays was possible. However, a comparatively exact inclined probe model could be gradually approached with the finite element program FEFLOW by WASY. Each BHE was divided into 10 sections, which were vertically positioned according to the present geometry and linked to one another.

The diagrams in Figure 17 show the simulated temperature distribution in January of year 10. The result is: An arrangement of the BHE as inclined star is advantageous for the heat extraction rate. The development of a large soil volume at depth has a greater influence on the extraction rate than the small distance between the probes at the top.

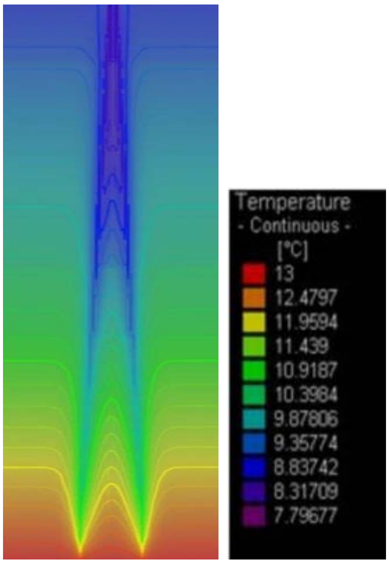

Figure 17: Numerical heat transport simulation of GeoStar with FEFLOW - temperature distribution in January of year 10.

3.5 Long-term monitoring

For long-term monitoring the GeoStar pilot plant was equipped with extensive measurement instrumentation to document flow rate, energy and temperature within the BHE field and at the heat pump station. Data is visualized and recorded via data loggers by the central building control systems together with further operating data of the building. The monitoring concept of the GeoStar comprises 34 temperature sensors installed at the inlet / outlet of G1 to G17 in the plenum and two vertical monitoring locations with measuring points at four different depth levels (5m, 50m, 100m, 150m) ensuring a continuous acquisition of subsurface temperatures within the BHE field. Applying temperature measurements to the central building control system facilitates an optimized and customized operating process of the geothermal system for heating and cooling. This way emerging reserves are used more efficiently for heating or cooling and an excessive heat input or withdrawal is counteracted. Also, the coefficient of performance (COP) including reservoir and distribution loss is evaluated and potential technical problems during operation can be identified and solved (e.g. leaky 3 way valves, non-stop operation of circulation system, unnecessary heat or cooling redistribution, etc.). In addition to continuous long-term monitoring of the geothermal system temporary measurements of the temperature field of the GeoStar during defined time intervals can be performed using the installed fiber optic temperature measurement technology. Along with 17 operational BHE G1-G17 monitoring wells M1 and G19 were equipped with fiber optic cables. As soon as comprehensive data from long-term monitoring are available the simulation model described above will be adjusted and validated.

4. CONCLUSION

The realization of the GeoStar prototype for the building project of the International Geothermal Centre (GZB) on the campus at Bochum University of Applied Sciences has verified that large powerful central geothermal systems with star-shaped deviated BHE are technically feasible in very small areas. The used drilling equipment, a 40 t mobile drilling unit with swiveling drilling rig, and the hydraulic down-the-hole-hammer drilling method are appropriate to drill deviated wellbores with depths > 200 m and install the corresponding inclined BHE. For dipping angles of not more than 10-15° technical modifications could be limited and the requirements for the deviated drilling technology were comparatively low. Solely rod handling had to be modified accordingly.

In general it has to be noted that dipping angles greater than 20° are not necessarily required in geothermal wellbores at intermediate depth levels ≥ 200 m in contrast to the established shallow geothermal radial drilling (eg GRD ® system manufactured by Tracto-Technik). For a radial arrangement dipping angles of 10° result in probe distances sufficient to reduce the mutual thermal influence of the probes significantly and to ensure an efficient heat extraction. Providing that a constant drilling direction can be maintained and a continuous measurement of the spatial orientation of the wellbores can be ensured, the GeoStar could have been extended gradually with up to 30 wellbores originating from one common soure point with dipping angles between 5-20°. Also, the drilling depth could have been increased. If required, significantly greater drilling depths are technically feasible with the used drilling equipment. It appears quite realistic that larger GeoStar systems can be installed in the future with dimensions of 5,000 to 10,000 meters per source point. Such a GeoStar could provide a geothermal capacity of up to 500 KW when used monovalently under medium to good geothermal site conditions. Accordingly, geothermal heat can be provided for large developing areas or office blocks with space to be supplied at the order of 10,000 m².

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