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# Theory and application of geothermal Energy

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ABSTRACT: In times of global warming renewable, green energies are getting more important. The development of application of geothermal energy as a part of renewable energies in Germany is a multidimensional process of fast growing improvements. Our institute is performing a research program supported by the Federal Ministry of Economics and Technology (BMWi) since May 2010. The main objective of this research program is titled "experimental investigation for the verification of a Finite-Element-Multiphase-Model for heat transport processes in the ground" whereby the subsoil is analysed as a three-phases-model with separate consideration of conduction, convection and their subsequent interaction.

The theoretical background of geothermal energy as well as basic principles needed for application orientated improvements is shown in this paper. The heat transport equation for water saturated geothermal systems is derived.

Furthermore, information on geothermal energy application especially in Germany is given. On basis of the theoretical background the current application of geothermal energy in Germany is shown. Therefore outstanding shallow geothermal projects such as different German high-rise buildings using geothermal energy for their energy demand as well as latest German geothermal power plants producing electricity from geothermal energy is discussed. The geothermal experimental investigation in field and in laboratory performed due to our research program is described in the paper.

## 1 INTRODUCTION

Geothermal energy is energy stored below earth's surface. The word geothermal is derived from the Greek words geo (earth) and thermos (heat), and combining these two meanings yields "earth heat". Although geothermal energy is one of the youngest types of renewable energy, it is certainly auspicious. While other renewable energy sources depend on the sun, geothermal energy originates in the earth's interior. This underground heat generation is caused mostly by the radioactive decay of persistent isotopes. On average, the temperature increases 3°C every 100 m of depth. This increase in temperature with depth is called the geothermal gradient. Therefore, 99 % of Earth is hotter than 1.000°C, while 99 % of the remaining 1 %is even hotter than 100°C. This vast geothermal energy reservoir can be exploited with the aid of suitable methods. Therefore, the assignment of geothermal engineers is to explore these areas and develop them for use to cool / heat buildings and generate electricity.

## 2. THEORY

The geothermal heat transfer can be derived from the first law of thermodynamics for a closed system, which can be written as (1).

$$dU = \delta Q + \delta W \quad (1)$$

Between any two equilibrium states the change of the inner energy $dU$ is equal to the sum of change of energy by a heating process $\delta Q$ and the change of work done $\delta W$ at the system. Derivation and transformation of (1) leads to (2).

$$\rho c \frac{\partial T}{\partial t} = -div(\dot{q}) + \dot{W} \quad (2)$$

- ρ density [kg $m^{-3}$]
- c spec. heat capacity [W s $kg^{-1}$ $K^{-1}$]
- T temperature [K]
- t time [s]
- $\dot{q}$ heat flux [W $m^{-2}$]
- $\dot{W}$ thermal source [W $m^{-2}$]

The change of the temperature T in time is heat flow density plus thermal sources while heat flow always occurs from a higher-temperature object to a cooler temperature as described by the second law of thermodynamics, indicated by the negative first right hand term. After all different types of heat flow mechanisms can be distinguished, such as conduction, convection and radiation. The conductive heat transfer bases on Fourier´s law and can be written as (3).

$$\dot{q}_{cond} = -\lambda \cdot grad(T) \quad (3)$$

- λ thermal conductivity [W $m^{-1}$ $K^{-1}$]

The convection (here transport of heat energy by groundwater movements) bases on the analogous Darcy´s law and can be written as (4).

$$\dot{q}_{conv} = (\rho c) \cdot div(vT) \quad (4)$$

- v Darcy velocity [m $s^{-1}$]

Heat transport by thermal radiation is defined as (5). For temperatures (8 – 15°C) of shallow geothermics radiation is less than 1 % of the total heat transport and can therefore be neglected Farouki (1986).

$$\dot{q}_{rad} = \varepsilon \cdot \sigma \cdot T^4 \quad (5)$$

- σ Stefan-Boltzmann-constant [W $m^{-2}$ $K^{-4}$]
- ε relation of emissivity [-]

Each phase of the multiphase body soil has its own combination of heat flow mechanisms. If heat flow by radiation is neglected the heat transfer equation for the fluid phase (index F) can be written as (6).

$$(\rho c)_F \frac{\partial T_F}{\partial t} = -(\rho c)_F v_F div(T_F) + div(\lambda_F grad(T_F)) + hA(T_S - T_F) + \dot{W}_F \tag{6}$$

h heat transfer coefficient [W $m^{-2}$ $K^{-1}$]
A area [$m^2$]

While the heat transfer equation for the solid phase (index S) of a multiphase body can be written as (7).

$$(\rho c)_S \frac{\partial T_S}{\partial t} = div(\lambda_S grad(T_S)) + hA(T_F - T_S) + \dot{W}_S \tag{7}$$

Current numerical programs based on the Finite-Element-Method (FEM) or the Finite-Difference-Method (FDM) describe the geothermal energy transport with different assumptions. These methods combine equation (6) and (7) with the assumption, that the temperature level of the fluid and the solid phase is equal (local thermal equilibrium). Furthermore, the thermal conductivity, density and heat capacity are uniformed from separated values of each phase to total values of the multiphase body (index SF). With these assumptions (6) and (7) can be written as (8) introducing the porosity n, which describes the ratio of pore volume to the total volume.

$$(\rho c)_{SF} \frac{\partial T}{\partial t} = -(\rho c)_F n v_F div(T) + div(\lambda_{SF} grad(T)) + \dot{W}_{SF} \tag{8}$$

n porosity [-]

With (8) the energy transport processes of deep geothermal systems (such as power plants) and shallow geothermal systems (such as borehole heat exchangers for heating or cooling buildings) can be analysed with help of numerical methods.

## 2 APPLICATION

### 2.1 DEEP GEOTHERMAL SYSTEMS IN GERMANY

Deep geothermal systems do primary depend on the quality of the geological source. Geological reservoirs of high geothermal quality are called high enthalpy reservoirs. The locations of these high enthalpy reservoirs correspond mainly to the Ring of Fire, the zone of frequent earthquakes and volcanic eruptions bordering the Pacific Ocean. The risk of failure of high enthalpy geothermal projects in this zone is very low. The risk of failure increases with geological uncertainty.

The first deep geothermal systems (geothermal power plants) were developed in high enthalpy reservoirs. The geothermal gradient in these reservoirs were outstandingly high, such that natural steam (dry or wet) could be used directly in primary power plants. Therefore, the first geothermal power plants in the world were dry steam and flash steam power plants.

Most countries in the world, including Germany, have no high-enthalpy reservoirs within their territory. To generate geothermal power, binary power plants must be installed. In these power plants, a binary fluid is evaporated and routed to a steam engine in a binary cycle. These systems are named Organic Rankine Cycle (ORC) or Kalina Cycle.

The first geothermal power plant in Germany was developed in Neustatdt-Glewe in 2003. Neustadt-Glewe is not located in a high-enthalpy region or a geological hot spot. At this site, water with a temperature of 98°C is pumped from a production well with a depth of 2,200 m.

Currently, the geothermal power plant in Neustadt-Glewe has an output of up to 230 kW. This plant demonstrates successful geothermal power production from 98°C fluid.

The ORC power plant Landau was developed in 2007. With its low-enthalpy temperature of 160°C, about 3 $MW_{el}$ are produced (Figure 1).

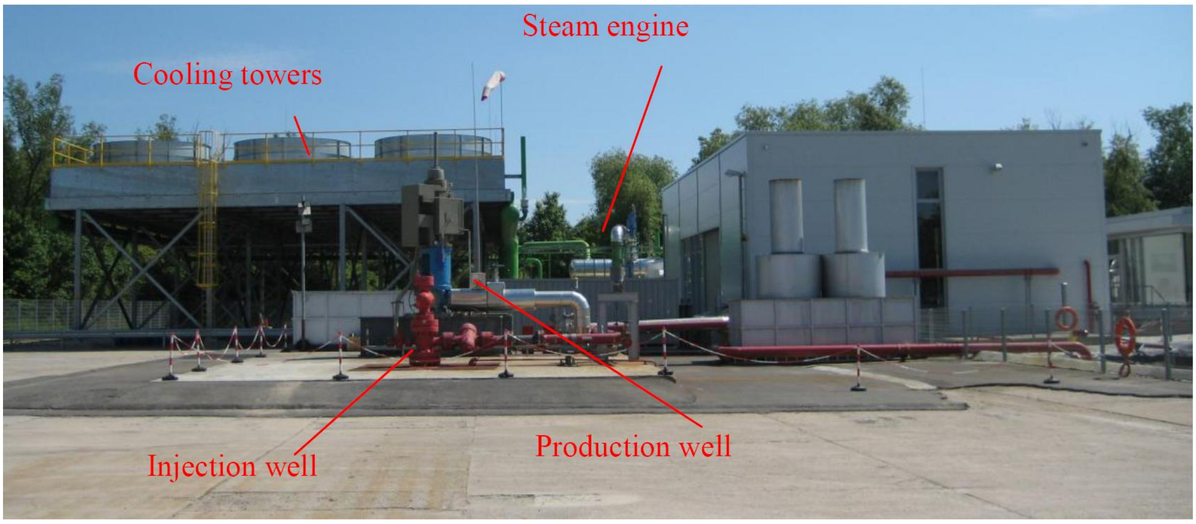


Figure 1. Geothermal power plant Landau

Landau is located in the geological anomaly zone called Oberrheintalgraben. Because of this anomaly, there is a geothermal gradient of about 4.7°C/100m, leading to a bottom hole temperature of 160°C at a depth of about 3,300 m. The geothermal power plant in Landau was the first profitable geothermal power plant in Germany.

Groß-Schönebeck is located in the northeastern region of Berlin. A geothermal research center was built upon a former site of petroleum gas drilling by the GeoForschungsZentrum Potsdam.

The GeoForschungsZentrum Potsdam, Germany's National Research Center for Geosciences, is working on making geothermal energy sources in the lowlands of northern Germany suitable for electricity generation. New procedures of tapping deep sandstone are being developed, particularly for use in a 4,300 m deep borehole formerly used for petroleum and natural gas. The aborted drilling was reactivated in 2000 and deepened to its final depth of 4,309 m. A second borehole was drilled at the beginning of May 2006, and stimulation techniques were tested and performed across the two boreholes.

The geological conditions in Groß-Schönebeck correspond to most European low-enthalpy regions. Therefore, Groß-Schönebeck was predestined for developing stimulation methods for suitable geothermal power generation in low-enthalpy regions with geological conditions similar to those in most of Europe.

At the site of Groß-Schönebeck, a research program for hot-dry-rock (HDR) geothermal power plants was initiated. In addition to stimulation methods, the sustainability and the long-term value of geothermal reservoirs were researched and improved.

The Kalina-cycle power plant Unterhaching was developed supported by national universities and government (state-aided) organizations. Using Kalina-cylce technology, water at 120°C from an aquifer with a depth of 3,500 m is used to produce about 4 $MW_{el}$ and 30 $MW_{th}$.

Unterhaching is located near Munich. The geological, hydrogeological and geothermal conditions of Munich are quite different from those of the aforementioned projects near Berlin (Groß-Schönebeck), northern Germany (Neustadt-Glewe) and the Oberrheingraben (Landau). In the case of the geothermal power plant located in Unterhaching, the main geologically homogeneous regions suitable for geothermal use are being investigated and researched in pilot projects.

## 2.2 SHALLOW GEOTHERMAL SYSTEMS IN GERMANY

Shallow geothermal systems are well probed in different projects in Germany for the heating and cooling buildings. Examples of different systems are open groundwater usage (WestendDuo, Frankfurt), groundwater heat storage (Reichstag, Berlin), field of borehole heat exchangers (municipal building, Frankfurt), and earth affected structures (Skyper, Frankfurt) integrated with the concepts of construction and heating/cooling. The shallow geothermal systems used for the heating and cooling of German reference buildings are pointed out in the following to explain the status quo of shallow geothermal applications.

The heating and cooling of the high-rise reference building WestendDuo in Frankfurt is supported by geothermal energy. Groundwater at a temperature of about 18°C is produced by two wells at a flow rate of 43 m³/h. The temperature level of the withdrawn fluid is raised by a heat pump, used, and reinjected into the ground in three injection wells. The system is defined as an open loop system, because both the energy of the ground and the groundwater itself are extracted. The concept of the open loop system is shown in Figure 2.

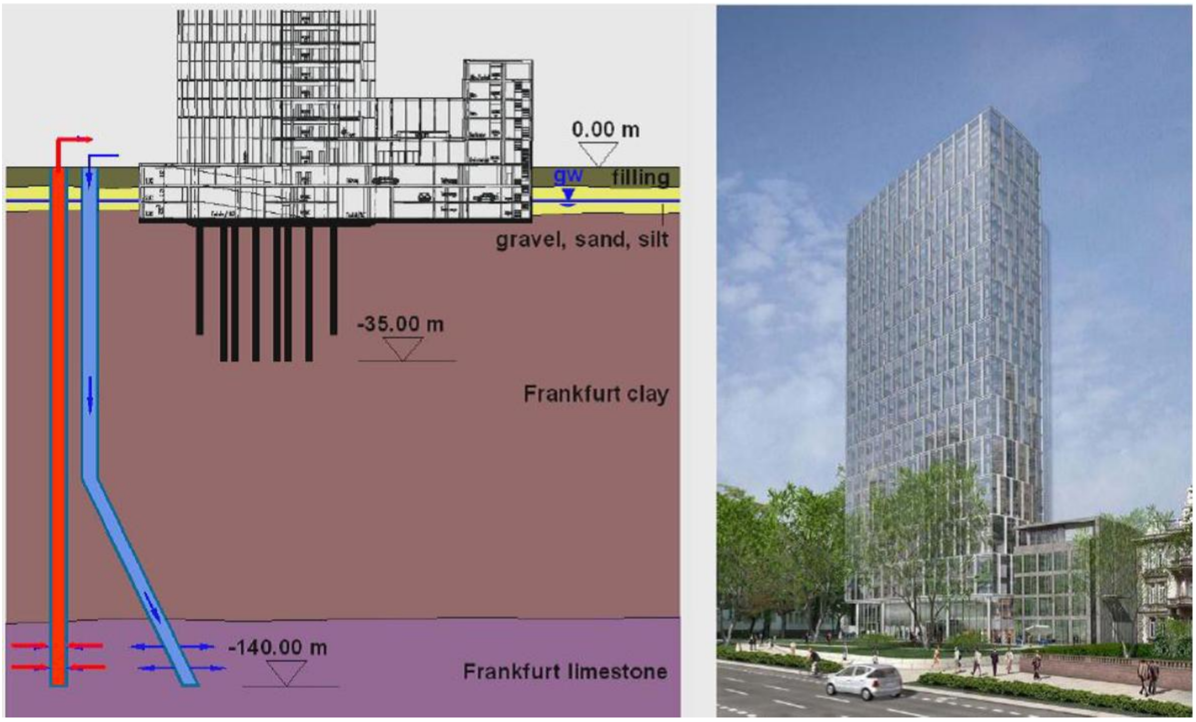


Figure 2. Heating/cooling system of WestendDuo, Frankfurt

Another German reference building that uses geothermal energy is the Reichstag building in Berlin. The Reichstag has been the seat of the German House of Parliament since 1995. The climate concept is based on a geothermal groundwater heat storage system. This groundwater heat storage system is used to heat and cool the innovative building. In the summer, excessive heat is carried by fluid at 70°C into a subsoil heat reservoir at a depth of 300 m. During periods of peak demand in winter, the stored heat is able to be recovered. Even then, the regained water temperature is up to 65°C. Additionally, a second groundwater reservoir at a depth of about 50 m is used for storage of lower temperatures (“cold storage”). An open loop system is also used in the Reichstag.

The municipal building in Frankfurt was built in 2008. Its heating and cooling is supported by geothermal energy. 112 borehole heat exchangers (BHE) are used to generate 600 kW of heating and cooling power. These BHEs are installed with a length of 85 m each, corresponding to a total absorber length of about 9,500 m. Inside the BHEs, a fluid is run through high-density polyethylene

(HDPE) tubes, gathering the heat of the surrounding ground via conduction. This shallow geothermal system of borehole heat exchangers is defined as a closed loop system, because only heat is extracted.

The high-rise Skyper building is located in Frankfurt. The 151 m high office building was built in 2004 and is supported by earth affected structures (energy piles). HDPE tubes with lengths up to 35 m were installed in the foundation piles. 30 km of HDPE tubes support the energy system in the building, which corresponds to a cooling power of 160 kW, a heating power of 300 kW, and a CO2 reduction of about 90 tons per year. The heating and cooling of the Skyper building with energy piles is illustrated in Figure 3, Quick et al. (2007).

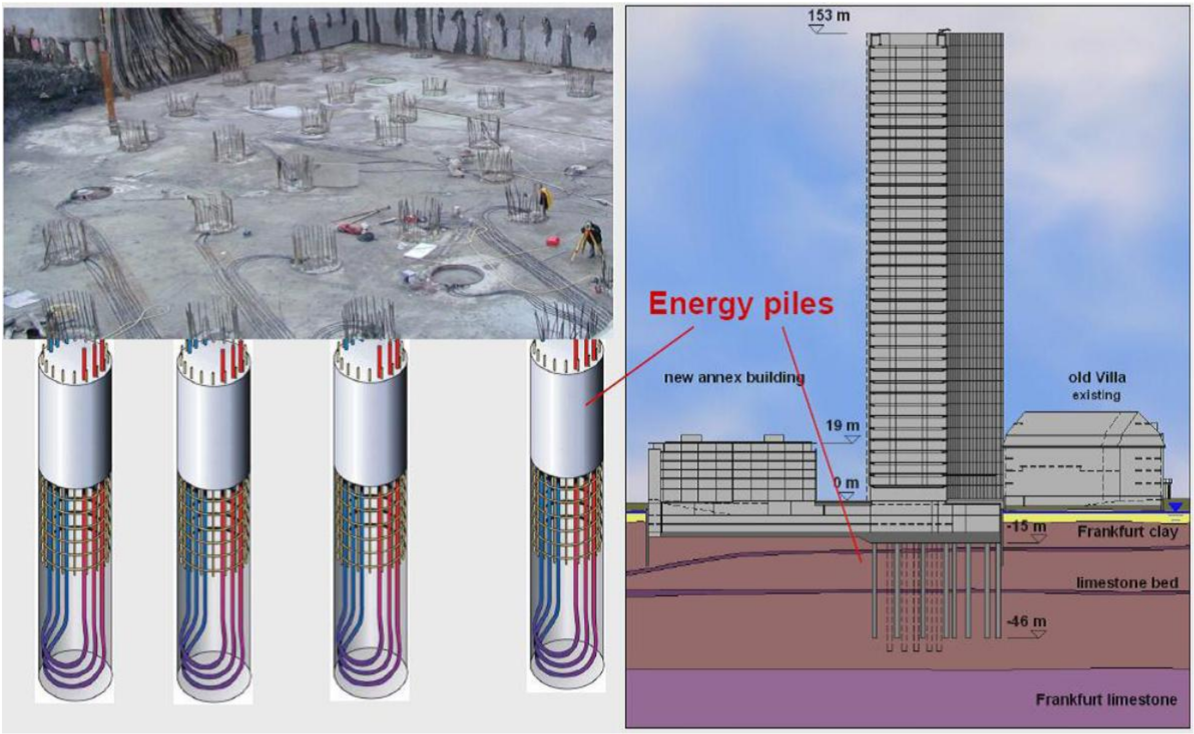


Figure 3. Climate concept Skyper, Frankfurt

## 5 CURRENT RESEARCHES

Currently our institute is performing a research program supported by the Federal Ministry of Economics and Technology (BMWi). The main objective of this research program is titled "experimental investigation for the verification of a Finite-Element-Multiphase-Model for heat transport processes in the ground" whereby the subsoil is analyzed as a three-phases-model with separate consideration of conduction, convection and their subsequent interaction. Therefore, extensive experimental laboratory as well as field tests is presently conducted at the Technical University Darmstadt (TUD).

To investigate the different types of heat transport mechanisms in detail a large scale laboratory apparatus has been developed at the TUD. The laboratory apparatus is constructed in a large scale with outer dimensions of 312 cm / 76 cm / 90 cm (L/W/H) and inner dimensions of 297 cm / 64 cm / 71 cm (L/W/H). The construction is very massive with an acryl glass wall of 1.5 cm supported by a steel frame in a U 80 shape placed vertically every 50 cm and horizontally at the top and the bottom. The apparatus is covered by an acryl glass plate. Every wall, the bottom and the cover plate as well as its connections are waterproof up to a high pressure.

The apparatus can be filled with different kind of water saturated soil. With its massive construction confined water of high pressure can be simulated.

At about one third of the length of the apparatus (83.3 cm) a line source is installed vertically. With help of this line source a thermal load can be applied to the installed soil steady or transient in time. With an extensive measuring system the temperature plum can be determined in dependence of the chosen Darcy velocity and the thermal load, Huber et al. (2011).

In addition to the laboratory tests geothermal field tests are currently conducted at two field test sites in Germany. Geothermal Response Tests (GRT) as well as Enhanced Geothermal Response Tests (EGRT) are performed in different geological and hydrogeological conditions In Figure 4 the field test site in Berlin Strausberg, is shown. On site 4 groundwater standpipes (B 1 – B 4) are installed in line surrounding borehole heat exchanger 6 (BHE 6). With the help of the groundwater standpipes, unequal surrounding hydraulic heads are set to BHE 6 in order to investigate the performance of GRTs and EGRTs depending on the forced groundwater flow Huber & Arslan (2012).

The geological conditions on site can be summarized as follows: Covered by 6 m of gravely sandy fillings, an impermeable marl layer was investigated up to a depth of 21 m below ground. The marl is followed by a 4 m layer of coaly sand covering a loose sandy gravel layer up to the maximum drilling depth of 50 m. The loose sandy gravel package is only interrupted by a thin layer of marl in a depth of about 46.20 m – 47.50 m below ground. Confined groundwater was encountered in all groundwater standpipes with an energy level of about 10.8 m below ground. The measured natural hydraulic gradient i between B 1 and B 2 is 0.007.

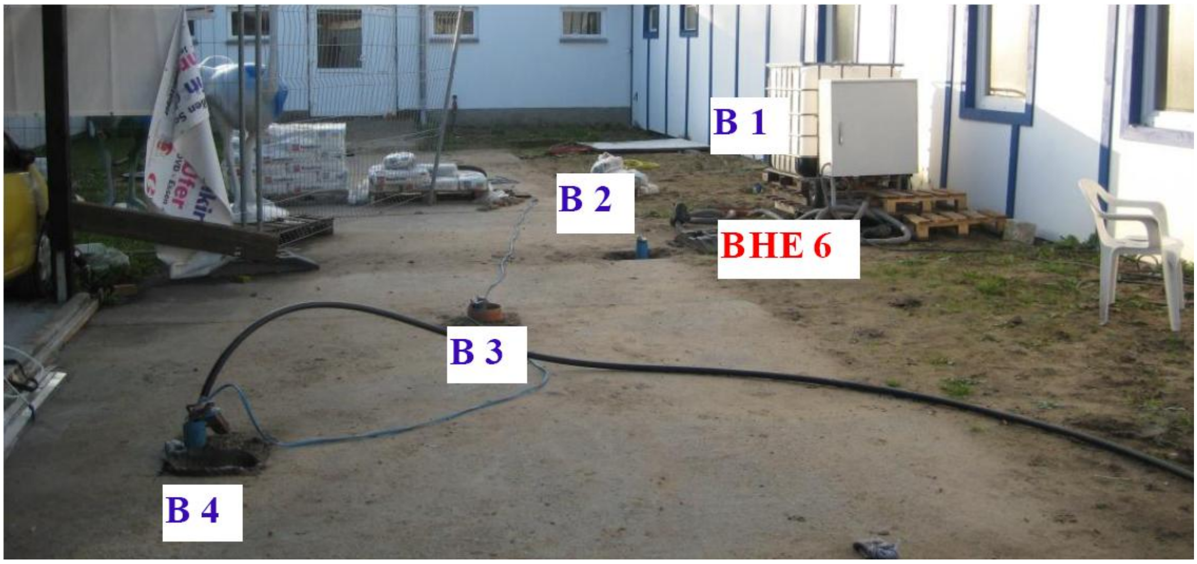


Figure 4. Effective thermal conductivity over depth

Three Enhanced Geothermal Response Tests (EGRT) were performed at BHE 6 in July (EGRT 1), October (EGRT 2) and November (EGRT 3) 2011. The thermal load was fed on BHE 6 with the help of a Geothermal Response Test (GRT) device. Therefore, the results of the EGRTs can be validated by the results of the common GRTs. The GRT device was connected to one of the double-U pipes and a constant thermal load of 52.3 W $m^{-1}$ (EGRT 1), 46.0 W $m^{-1}$ (EGRT 2) and 41.5 W $m^{-1}$ (EGRT 3) was applied for 62 h (EGRT 1) respectively 70 h (EGRT 2, EGRT 3).

While EGRT 1 was performed without any groundwater extraction, EGRT 2 was carried out at the steady state of Pumping Test 1 with a pumping rate of 3.4 $m^3$ $h^{-1}$ and EGRT 3 was carried out at the steady state of Pumping Test 2 with a pumping rate of 7.5 $m^3$ $h^{-1}$ (EGRT 3).

As a result of the EGRT the temperature development for every incremental depth of the BHE 6 can were measured.

According to the slope k of the temperature development, the effective thermal conductivity over depth can be determined by the Source Theory. The determined mean effective thermal conductivity increases according to the applied groundwater flow velocities from 2.11 W $m^{-1}$ $K^{-1}$ (EGRT 1) to 2.37 W $m^{-1}$ $K^{-1}$ (EGRT 2) and 2.49 W $m^{-1}$ $K^{-1}$ (EGRT 3). That means an increase of 12.3 % respectively 18.0 %.

Especially in the gravely, sandy aquifer layer (21 m – 46.2 m), where groundwater flow occurs, a high increase of the effective thermal conductivity of 13.3 % (EGRT 2) and 21.9 % (EGRT 3) can be observed. According to singular flow paths in the aquifer an increase of the effective thermal conductivity in chosen incremental depths of even 16.6 % (EGRT 2) and 32.2 % (EGRT 3) can be determined (Figure 5).

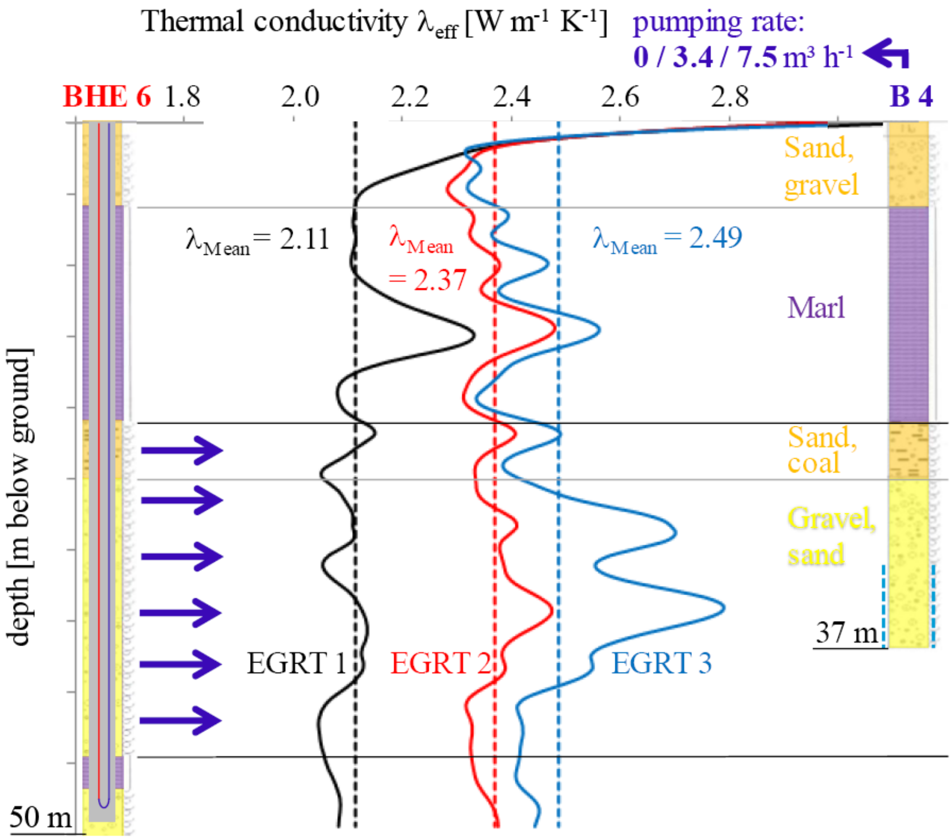


Figure 5. Effective thermal conductivity over depth

Currently all the results of the field tests are compared to the performed laboratory tests and reanalyzed with numerical methods.

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