Comparative temperature measurements in an experimental borehole heat exchanger

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ABSTRACT

Temperature measurements in vertical borehole heat exchangers (BHE) are now common practice in the building industry. They are used for the design of BHE installations, as well as for quality control purposes, for instance in detecting the presence of groundwater circulations. In the city of Zollikofen (CH), a BHE-array is planned for heating and cooling a retirement home. In the design phase, a pilot BHE was drilled. For technical reasons, the pilot BHE will not be connected to the final system. The opportunity to rehabilitate the pilot BHE has therefore been seized for the purpose of installing an experimental BHE that can be permanently accessed for measurements and experiments. The SwissEnergy Programme initiated some projects to increase the execution quality of BHE in Switzerland. In this framework, the experimental BHE has been used to compare seven commercially available temperature logging devices. The results indicate that all seven measurements show a high level of congruency all along the profile. Deviations are mainly explained by an inadequate measurement speed with respect to thermal reactivity of the sensor. Current commercially available devices are suitable for temperature measurement in BHE only if the operator respects the recommended measurement speed. These devices are very reliable and provide accurate information about the sub-surface temperature that could be used either in the design of BHE or for quality control purposes.

1. INTRODUCTION

The use of Borehole Heat Exchanger (BHE) technology for heating and cooling has been steadily developing in Switzerland in recent decades. Due to the extremely competitive business environment, the price per meter of BHE execution has decreased continuously while the risk of low quality of execution has increased. As a consequence, the SwissEnergy Programme has been initiating and encouraging projects to increase the quality of BHE execution in Switzerland. These projects concern the planning of BHE but also the execution itself and range from device development (such as temperature measurement devices) to innovative methodologies, policies and field inspections.

Knowledge of the underground temperature is critical for quality and cost effectiveness of BHE installations. Temperature data are used as a key input parameter for the design of large BHE arrays and for control purposes during the execution and operation phases. These measurements can also be used as a diagnostic tool in cases of functionality deficiencies and for identifying the presence of groundwater circulations.

For the reasons mentioned above, temperature measurements in BHEs are currently a common practice in the building industry. Due to their simple execution and relatively low costs, temperature measurements are an appropriate tool for solving initial uncertainties and will most likely be further developed within the next few years.

A study to evaluate the quality of temperature measurements in BHEs has therefore been initiated by the Swiss Federal authorities in the framework of the SwissEnergy Programme (Badoux et al 2016). The aim of this study is to systematically compare temperature profiles in an experimental BHE made with different measurement devices available on the market. Through this comparison, the quality of the different temperature measurements can be assessed. Further, the results of the study could be used as a benchmark for further control of temperature devices or other technologies.

In practice, characteristics and time schedules of construction projects usually do not allow comparative temperature measurements. First, newly installed BHEs are usually freely accessible for a very restricted period before they are connected to the heating loop, and an undisturbed temperature profile should be not be executed prior to 8 to 10 days after the installation of the BHE. Second, any measurements in a BHE risk damaging the installation, for example if the measuring device is lost in the borehole. Temperature measurements are therefore only executed in cases of absolute necessity, for instance for planning or quality control purposes. Finally, the costs of planning, executing and

interpreting the measurements are usually too high for small BHE installations. For these reasons, temperature measurements are usually executed only for large BHE installations (more than four BHEs). Comparative temperature measurements are usually not feasible.

2. EXPERIMENTAL FIELD SITE

In the city of Zollikofen (Switzerland), a BHE array composed of 30 BHEs was drilled in 2014 for heating and cooling a retirement home. During the planning phase, a pilot BHE was drilled down to a depth of 250 meters. The pilot BHE was equipped with a standard PE double-U pipe 40 mm in diameter. A standard Thermal Response Test (TRT) was carried out at that time. The BHE array will be connected to the heating system in early 2017.

For technical reasons, the pilot BHE will not be connected to the final system and therefore will not be in operation. In 2015, GEOTEST Ltd rehabilitated the pilot BHE in order to transform it into an experimental BHE field site.



Figure 1: Fiber optic cable (in red) installation at the BHE experimental field site in Zollikofen (Switzerland). Pilot BHE (left) and Distributed Temperature Sensing system (right).

The pilot BHE was cleaned and a concrete ring with a removable metal cover was installed for protection and permanent access to the pipes (Figure 1). Since the pilot BHE is not located on a construction site, it has the advantage of being permanently accessible without any special authorizations or equipment, and there is no risk of disturbing construction activity. Moreover, it will continue to be accessible during the operation of the BHE array.

The pilot BHE was permanently equipped with an optical fiber cable for Distributed Temperature Sensing (DTS) measurements. The optical fiber cable is connected to a building, which provides optimal conditions for operation of the DTS system (Figure 1).

The experimental field site is used for research and development, for testing and comparing logging devices, for demonstration purposes and for teaching.

3. TESTED TEMPERATURE DEVICES

At present, seven different types of temperature sensing devices have been tested and compared in the BHE experimental field site. Since the objective of this study is to compare the results of measurements obtained by different types of devices and not to assess the data quality provided by specific devices, the names of the device models and the names of the logger companies are not mentioned explicitly in this paper. Each device is designated by a single capital letter A to G (Table 1).

Table 1: Classification of temperature devices tested and compared in this study.

Category	Device Type	Device ID
I	Cable-free	A & B
	Cable-mounted	C & D
	Hybrid	E & F
II	Fiber Optic Cable	G

In this study, two main categories of devices were tested (Table 1). The first category includes classical logging devices (devices A to F), which measure temperature using a classical thermal sensor. The device is pulled down into the U-pipe and measures the temperature at regular time intervals. The second category consists of devices based on fiber-optic cable technology.

While all devices of the first category differ slightly in terms of construction and design, the main differences relate to the presence or absence of a cable and to the method used for depth characterization.

The devices in the first category are classified either as cable-free devices or cable-mounted devices (Table 1). The principle of cable-free devices (devices A & B) is to store the data directly in the device (Figure 2). The energy supply is also fully integrated within the device. Cable-free devices typically measure the temperature together with hydraulic pressure, and the pressure is then converted to depth. The devices are brought back to the surface by flushing them out of the U-pipe. According to the manufacturers, cable-free devices are easier to operate and provide less temperature disturbance than cable-mounted devices because they only displace a small volume of water within the pipe. The submersion velocity depends on the density of the device, the pipe diameter and the fluid viscosity. In a PE pipe 40 mm in diameter filled with water, velocities are typically between 0.1 and 0.3 m/s, depending on the particular device. The submersion velocity is a key feature of the device since its design must be coordinated with the thermal reactivity of the temperature sensor and the device.

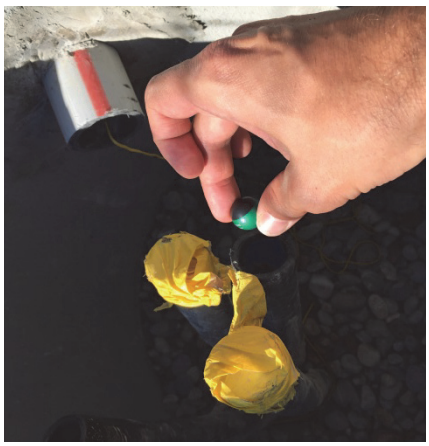

Figure 2: Illustration of a cable-free device.

For cable-mounted devices (devices C & D), the cable usually has three functions. First, it transfers energy from the energy supply unit to the device. Second, it transfers data from the device to the operating unit. Finally, it can be handled and is used to pull the device back up to the surface. The cable can be controlled manually or by motor. Motorized winches provide precise control of the submersion velocity, which can be adjusted as appropriate for the thermal reactivity of the device. For cable-mounted devices, the depth is usually measured in terms of running meters (measured depth, MD), which needs to be converted into true vertical depth (TVD). The handling of cable-mounted devices is more complex than cable-free devices, and there is a higher risk of the device becoming stuck in hole, due to friction between the cable and the PE pipe. The main advantage of cable-mounted devices is the possibility of real-time monitoring of the temperature during the measurements.

Devices E and F are classified as hybrid devices (Table 1). They are cable mounted, but the data and energy are directly stored within the device. The cable is therefore only used to hold the device, control the submersion velocity, and pull the device back up to the surface. Hybrid devices have the advantage that they can measure the hydrostatic pressure and the cable length simultaneously, which enables cross validation of the measurement depth.

The last category of devices is based on fiber optic technology (device G). Fiber optic cables can be installed permanently or temporarily within the U-pipe or within the filling material. In the BHE experimental field site, the fiber optic cable was installed after completion of the BHE. The measurement principle of this type of device is based on Raman spectrometry (Ahangrani and Gogolla 1999), where a laser sends a pulse signal into the optic cable. A so-called Distributed Temperature Sensor (DTS) analyzes the reflection and the phase shift of the signal. Both parameters depend on the distance and the temperature. The DTS interprets the recovery signal and provides the temperature as a function of the distance to the laser source. Depending on the power capabilities of the laser, temperature can be measured with a spatial resolution of up to 1 m over several km of distance.

4. RESULTS

Seven temperature measurements were logged in the BHE experimental field site, each using a different type of temperature sensing device. The temperature measurements were completed within the period between 25.08.2015 and 09.12.2015. The different temperature logs are presented in Figure 4. Temperatures are summarized in Table 2 for the selected depths of 50 m, 100 m, 150 m and 225 m.

The study shows that all seven measurements were congruent to a large extent along the entire investigated depth interval.

First, the results show that all tested devices are capable of measuring the temperature down to the deepest point of the BHE. The maximum depth measured by the devices ranged from 233.7 to 235.2 m.

As indicated by the temperature logs, the comparative measurements showed strong variations within the first 20 meters. This confirms the influence of seasonal variations in the surface temperature down to a depth of around 20 m, which is typical for conditions in Switzerland (Medici and Rybach 1995).

Below 20 m, all measurements showed consistent temperature profiles. The minimum temperature of around 12°C was located at a depth of around 67 m. Deeper than 67 m, the temperature increased to a maximum of around 16.5°C degrees at the final depth of the BHE. The measured temperature gradient of 3.4°C/100 m is consistent with the average geothermal gradient in Switzerland (Medici and Rybach 1995). The temperature measurements indicate that the geothermal gradient in the experimental BHE is not constant, due the heterogeneity of the encountered rock lithology (with varying thermal conductivity) and the presence of groundwater circulations. These aspects will not be discussed further in this paper.

Although all temperature logs showed comparable behavior, some differences between the measurements and the device types were observed. The main differences are described below.

The difference between the maximum and minimum temperature measured with different device types at certain depths ranged from around ±0.45 K at 20 m depth to ±0.35 K at the maximum depth. No significant trend regarding these differences was observed.

Although the trends occurring in the temperature logs were generally consistent, the temperature logs obtained with devices D and F showed a larger deviation from values logged by the other tested devices. By 50 m depth, the measurement of device D showed a deviation of +0.33K from the average

measured temperature over all devices (Table 2 and Table 3). With increasing depth, this deviation declined considerably. At a depth of 225 m, this deviation was smaller than +0.2 K. For device F, the deviation with respect to the measured temperature averaged over all devices increased with depth, up to a maximum deviation of -0.46K at 225 m depth (Table 2 and Table 3).

All other devices deviated by around ±0.1 K from the average measured temperature. At 50 meter depth, the standard deviation was reduced to 0.01 K (Table 3). Starting at 65 m depth, the standard deviation increased slightly and reached a maximum of 0.16 K at a depth of 225 m (Table 3).

Table 1: Results of comparative temperature measurements [°C] (Devices A to G) at selected depths

Device	50 m	100 m	150 m	225 m
A	12.18	12.51	13.65	16.33
B	12.17	12.43	13.50	15.98
C	12.17	12.48	13.60	16.16
D	12.55	12.74	13.74	16.30
E	12.19	12.47	13.61	16.25
F	12.05	12.17	13.23	15.62
G	12.17	12.50	13.54	15.96

Table 3: Average temperature [°C] and standard deviation (σ) of the results at selected depths

Stat.	50 m	100 m	150 m	225 m
Avg_{A-G}	12.22	12.47	13.55	16.08
σ_{A-G}	0.17	0.17	0.16	0.25
$\sigma_{A-C, E, G}$	0.01	0.03	0.06	0.16

5. DISCUSSION

The deviations observed between the different temperatures logs might have been caused by a difference in the temperature sensor calibration, the algorithm applied for the depth determination, or an inappropriate measurement velocity. Nevertheless, the observed deviations are considered very low. The results of the experiment described in this paper do not allow a differentiation between the performance of cable-mounted and cable-free devices, since all devices reached the final depth of the BHE with a similar level of accuracy. None of the tested devices remained trapped in the experimental BHE.

The submersion velocity during the measurement was probably the main reason for differences between the tested devices. If the submersion velocity is too high with regard to the thermal reactivity of the sensor, the device does not have enough time to reach a thermal equilibrium with the fluid. As a result, the measured temperature deviates from the real fluid temperature. This happened for devices D and F.

The measurements made by devices D and F show that the submersion velocity was too high in comparison to the thermal reactivity of the sensor. Device D was not able to capture the large temperature gradient in the upper part of the borehole. The operator of device D reduced the speed of the submersion in the lower part of the borehole, which allowed the measured temperature to slowly return to equilibrium with the real fluid temperature.

Device F was also operated at an inadequate speed until the final depth of the borehole. Since the device remained at the bottom of the BHE for a couple of minutes, the measured temperature equilibrated with the real fluid temperature (a compensation of around 0.5 K).

6. CONCLUSIONS

Comparison of depth-temperature profiles showed very good congruency among all the tested devices. In field conditions, the standard deviation of all measured temperatures was 0.25 K at a depth of 225 m.

The differences between the different device types were probably mainly due to differences in the speed of measurement with regard to the thermal reactivity of the device. Two of the tested devices clearly indicated that the measurement velocity was too high. Excluding these two devices, the standard deviation of the measurements was reduced to 0.16 K at 225 m depth. The accuracy of temperature measurements depends on the accuracy of the sensor, the execution of the measurement, and the interpretation of the results. In practice, the main source of inaccuracies is the execution of the measurement rather than the accuracy of the devices themselves.

The device types tested in this study are therefore suitable for temperature measurements in BHE. They are considered very reliable and provide accurate information about the sub-surface temperatures, which could be used for the design of BHEs or for quality control purposes. Attention should be given to the operating mode of the device and to the instructions given to the operator. The operator should strictly follow the instructions of the manufacturer or supervisor. The risk of operation error or inaccuracy is highest for manually controlled cable-mounted devices. Cable-free devices are only suitable for measurements in pipes with the diameters for which they are designed. The measurement protocol, together with the required submersion velocity, should be explicitly communicated to the client for better traceability of the results. Further tests of temperature devices and trajectory measurement devices are planned.

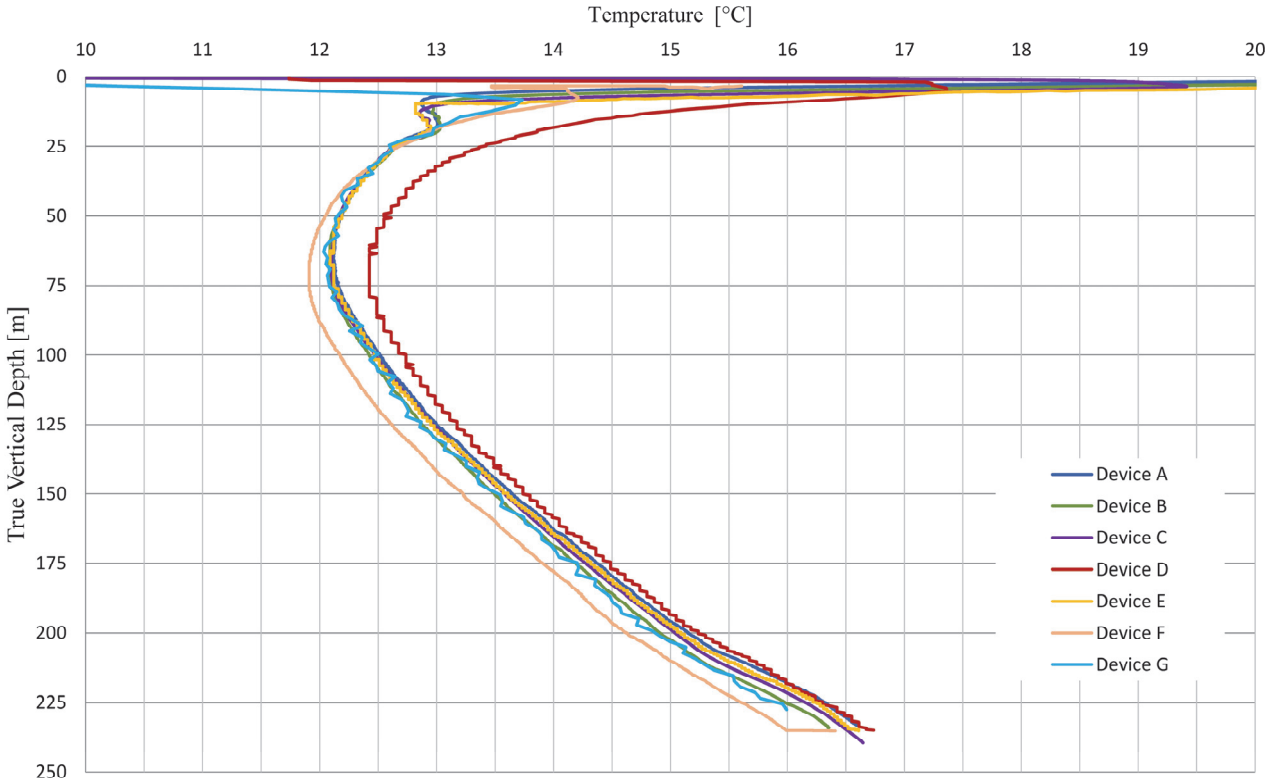

Figure 4: Comparison of temperature measurements

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