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Development of a new borehole probe for thermal conductivity scanning

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ABSTRACT

Knowledge about the thermal conductivity of rock is essential for accurate design of geothermal plants. Thermal conductivity can be measured in situ, with low precision and coarse spatial resolution, or in a laboratory, where samples are subject to altered conditions and represent only limited sections of the borehole. We have developed and evaluated a new technology involving fast, high-resolution, and high-precision scanning of in-situ thermal conductivity within boreholes. The prototype demonstrated the feasibility of the technology for shallow geothermic wells, with an accuracy of 10%.

1. Introduction

A new borehole probe was developed with the objective of measuring in-situ thermal conductivity with high speed, precision, and spatial resolution. The principle of thermal conductivity scanning (TCS) developed by Popov et al. (1983) was adapted for application to in-situ measurement.

TCS is a technology for measuring the thermal conductivities of borehole core samples in the laboratory. As with other laboratory techniques, the results are affected by issues such as samples altered by the temperature and pressure conditions in the laboratory and by the process of borehole sampling. Additional data, such as in-situ temperature, pressure, and water saturation, are required for the derivation of original conditions from laboratory measurements (Fuchs et al., 2013). These requirements, and the restricted informative value of the measurements, linked to limited borehole core sampling, reduce the applicability of TCS technology. Alternative laboratory methods for determination of thermal conductivity have the same problems, as described, for example, by Clauser (2011), Parker et al. (1961), Sass et al. (1971) and Vacquier (1985).

Currently, the thermal conductivity of rocks drilled by boreholes is mostly determined using in-situ techniques. For shallow boreholes, the thermal response test (TRT) is often used (Sanner et al., 2005), which is based on the line source principle (see Carslaw and Jaeger, 1959). Whereas in intermediate and deep boreholes modified versions of this principle are used, e.g. the ones developed by Burkhardt et al. (1995) and Kukkonen et al. (2007). However, these techniques do not solve the problem satisfactorily as they provide coarse spatial resolution, require a long duration test, and the results are affected by the borehole profile and anisotropy.

Innovative attempts to obtain the thermal conductivity of rocks in a geothermal context have been made by Eppelbaum and Kutasov (2013), Hartmann et al. (2005), Popov et al. (2011) and Prats (1982). These studies measured adequate in-situ and laboratory data using state-of-the-art methods for describing rock formation thermal conductivity and derived mathematical models for its systematic determination. They also pointed out the problems caused by the lack of adequate background data.

Using TCS technology in a borehole reduces the testing time from days (TRT) to several hours or minutes and improves the spatial resolution to the centimetre-level or even finer. Furthermore, predictions of surface roughness and calibre are possible.

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2. Concept of the probe

TCS laboratory measurement is based on a focused optical heat source traversing and heating one or two standards and the test specimen (Fig. 1). For an infinitesimally small heating spot and a constant velocity, the temperature rise of homogeneous bodies shortly after heating is reciprocal to their thermal conductivity. The influence of the volumetric heat capacity of the material is theoretically zero (Carslaw and Jaeger, 1959) and is negligible in the experimental set-up (Popov et al., 1983). For determination of thermal conductivity, the temperature before and after heating is measured by optical sensors. The thermal conductivity (λ) of the specimen is calculated based on Popov et al. (1983):

$$\lambda_{test} = \lambda_{ref} \cdot \frac{\Delta T_{ref}}{\Delta T_{test}}, \quad (1)$$

where λ_{test} is the thermal conductivity of the specimen, λ_{ref} is the thermal conductivity of the standard, ΔT_{ref} is the temperature rise of the standard and ΔT_{test} is the temperature rise of the specimen.

In a borehole, a range of factors may influence optical measurements. The rough wall of the borehole means the distance between the specimen and instrument varies; therefore, the focal distance varies. Boreholes are usually filled with formation- and/or drilling liquid, which is non-transparent for optical signals and light beams. In addition, hydrostatic pressure and space limitation in boreholes make measurement difficult. For equalizing the optical characteristics of the specimen surface in the laboratory, the specimen is painted black before measuring. This step is not possible in a borehole. Following Sauer (2015), the following measures were performed to solve the problems stated above (see Figs. 2 and 3):

- A measuring packer is inflated around the optical instruments, clearing the measuring area from liquid/mud.
- The packer consists of a thin rubber foil which forms a double layer with the wall during measurement. The optical heat source beams onto the inner side of the rubber foil, so that the heat passes through the rubber before it penetrates the rock.
- A laser is used as heat source to avoid defocusing.
- To avoid destructive buoyancy on the measuring packer, a fixing packer is installed above the measuring packer.
- For centralizing, a third packer is installed below the measuring packer.
- The pneumatic system is supplied by one pneumatic block, with all valves in the top of the probe.
- As a safety measure, the optical components are fixed in a sensor casing in case the thin rubber foil bursts.
- During measurement, a hydraulic system moves the sensor casing at a constant velocity along the 1-m scanning line.
- For tool control and data transmission, the probe is connected to a computer at the surface via control card and LAN-USB-converter inside the hydraulic chamber.
- The hydraulic and pneumatic chambers and sensor casing are sealed and equipped with a pressure balance system.
- Temperature measurement is executed by infrared camera. This saves space in the sensor casing, avoids fitting of standards to specimen[1] and enables compensation for the varying distances between sensor and wall. Furthermore, the camera measures additional information which can be used to determine the thermal diffusivity of the rock.
- Additionally, the sensor casing is equipped with an optical triangulation tool for compensating for the influence of varying distances and for automating measurements.
- Markers on the sensor casing allow determination of its position during distance measurement, thus enabling determination of the velocity.
- For automation, four sensors are placed in the measuring area inside the measuring packer. They control the status of the packer and the sensor casing.

The described probe was realized in a prototype and tested step by step, first in the laboratory, then in a complex test stand and finally in a real borehole (Sauer, 2015).

3. Laboratory tests with the sensor casing

The sensor casing is the fundamental element of the probe, so it was produced and tested first. For the test, rudimentary control and data processing software was generated, and then the laboratory TCS was simulated. The aim of the test was to investigate if infrared camera, laser and distance measurements with similar precisions as the standard laboratory system were possible.

3.1. Methods

Test measurements were conducted in a laser safety laboratory. The sensor casing was mounted onto a linear motor and linked to a control computer. The scanning velocity was set at 1 cm/s, as is usual in the laboratory. Six standards of length 5–10 cm were fixed along the profile line. The standards had the following thermal conductivity (listed in the order they were measured):

- 3.81 W/(m·K) – Thassos marble
- 6.46 W/(m·K) – titan alloy
- 1.185 W/(m·K) – glass
- 1.185 W/(m·K) – glass
- 6.46 W/(m·K) – titan alloy
- 3.82 W/(m·K) – Thassos marble

The standards were borrowed from Lippmann & Rauen GbR, who produce and calibrate TCS technology in Germany, and the properties of the standards were exactly known. The first was used as standard in the evaluation, while the other five were used as specimens. Thermal conductivity was calculated using Eq. (1). A 'LDM-445-2000 Laser Modul' from 'Lasertack – New Laser Generation' was used, with beam power set at 0.7 W for the test, a beam diameter of 1 mm (minimum diameter of the oval) and wavelength of 445 nm. The long axis of the heating spot was oriented in the direction of movement and the laser worked in steady mode. A ThermoIMAGER TIM 160 from 'Micro-Epsilon' was used as a sensor. The camera works in an optical spectrum of 7.5–13 μm, so is not influenced by reflected laser light. No distance measurements were necessary for the test, as a constant distance of 5 cm was set between the optical instruments and standards. The standards were painted black using acrylic paint. A rubber foil was not used.

3.2. Results and discussion

The six standards were each measured 10 times over a short period. The results for the five test specimens are shown in Fig. 4. Overall, the measurement of thermal conductivity was successful, with a mean precision of 7.1% and mean accuracy of 7.6%. Standard deviations depend on the thermal conductivity; the higher the thermal conductivity, the higher is the standard deviation. The last specimen on the profile (3.81) shows a relatively high pre-

[1] In the laboratory, the thermal conductivity of the standard is iteratively selected as near as possible to that of the specimen, but this step is not possible in a borehole. The camera and an improved evaluation algorithm that enables the iterative process to be skipped, and one standard is used.