Results of Fibre Optic Temperature Measurements in Boreholes

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Motivation

The distributed optical fibre sensing technique represents a new physical approach for temperature measurements.
First results on applications of fibre optic temperature measurements in boreholes as well as for long-term temperature monitoring for studying geotechnical and environmental problems (e.g. waste disposal) are published by Hurtig et al. (1993, 1994) and Hurtig and Schrötter (1993).
It is the aim of this study to test the fibre optic sensing technique for its capability for long-term temperature monitoring in deep boreholes even under complicated conditions.
Two cases are studied:

- comparison between high-resolution temperature borehole logging and fibre optic temperature measurements in a monitoring borehole of the freezing shaft 1 in Gorleben.
- long-term stability of the measuring system installed permanently in the annulus between casing and tubings in a borehole of the underground gas storage Buchholz.

Method

- The distributed optical fibre temperature sensing technique is based on optical time-domain reflectometry.
- A pulsed laser is coupled to the optical fibre which is the sensing element.
- A small part of the light is backscattered as the pulse propagates through the fibre owing to changes in density and composition as well as to molecular and bulk vibrations.
- The backscattered light is guided back to the source and is split off by the directional coupler to the receiver.
- The backscattered light includes different spectral components (see Fig. 1).
- The Raman backscattering component is caused by thermally influenced molecular vibrations, its intensity is dependent on temperature and, thus, can be used to measure the temperature along the optical fibre.
- As the velocity of light propagation within the fibre is known, from the travel time of the backscattered Raman component the location of the backscattering centres along the optical fibre can be obtained.
- Thus, it is possible to determine simultaneously temperature and distance along the fibre.

The principle of distributed fibre optic temperature sensing is shown in Fig 2.

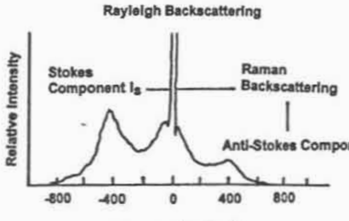

Fig. 1: Schematic Spectrum of Backscattered Light

The following relation holds:

$$I_a/I_s = \{(\kappa_0 + \kappa_k)^4/(\kappa_0 - \kappa_k)^4\} \exp(-hc\,\kappa_k/kT)$$

I_a: Intensity of the Anti-Stokes line	T: Temperature [K]
I_s: Intensity of the Stokes line	k: Boltzman's constant [J/K]
κ_0: wavenumber of the incident light [cm^{-1}]	h: Planck's constant [J·s]
κ_k: shift amount of wave-number [cm^{-1}]	c: light velocity [m/s]

Results

Since 1992 fibre optic temperature measurements were performed in several boreholes. Figs. 3 to 5 give two case studies. The used device for fibre optic temperature measurements includes the transmitting and recording unit, a portable computer for controlling and data analysis, and the fibre optical cable (Fig. 2).

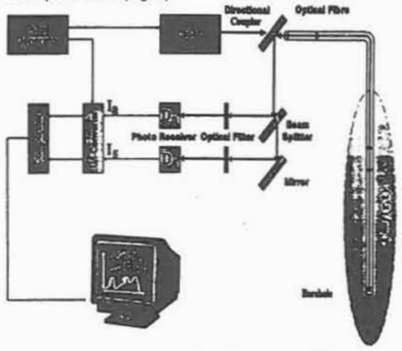

Fig.2: Principle of Fibre Optic Temperature Sensing

Fig. 3 shows the results of fibre optic temperature measurements in a temperature monitoring well of the freezing shaft Gorleben 1. The temperature varies between -12°C and -16°C. The crosses give the temperature at selected depth points measured by a high-resolution thermal device of the BGR. Both curves fit well within a 0.1 to 0.2 degree range. The surface of the salt dome is located at a depth of about 240 m. Thus, the temperature increases below that depth.
Fig. 4 shows the results for a 600 m deep production well in an underground gas storage. The fibre optic sensing cable is installed stationarily in the narrow annulus between the casing and the tubings. The temperature curves show the strong distortion of the temperature field caused by gas injection between September 9 and October 7. Since October 7 there was no injection or extraction, thus the equilibrium temperature could be re-established. The strong increase of temperature at a depth of about 20 m is caused by the fluid level in the annulus. The anomalies at a depth of 520 to 530 m are caused by rock salt layers with a high thermal conductivity. These anomalies fade out with time. The geothermal gradient (Fig. 5) for the individual geological formations increases while approaching the formation temperature.

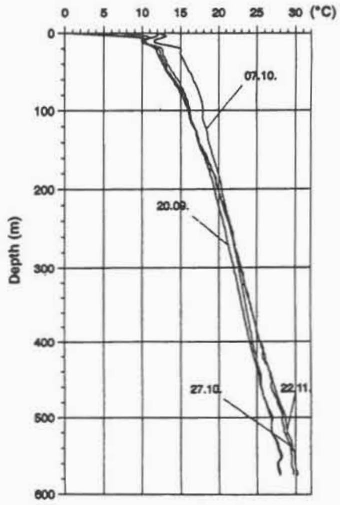

Fig.4: Temperature-depth curves

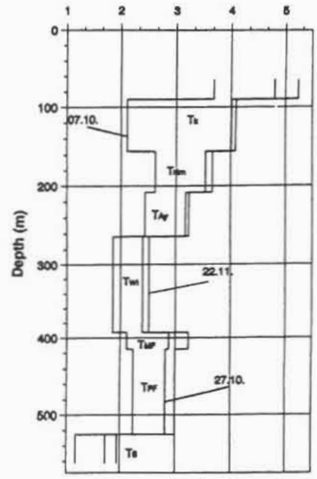

Fig.5: Variation of the geothermal gradient (°C/100 m) with time for the individual geological formations

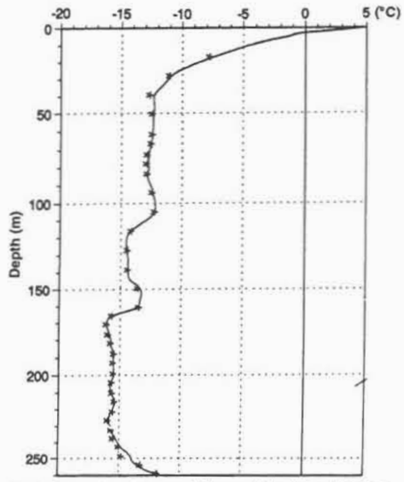

Fig.3: Comparison between high-resolution thermal logging (crosses) and fibre optic temperature measurements in a monitoring well of the Gorleben freezing shaft 1

Conclusion

From the measurements follows that the optical fibre temperature sensing technique can be used under field conditions. It is of special advantage that the fibre optic sensing cable can be installed stationarily even under conditions where thermal borehole probes can not be used. The system can be installed also in horizontal and inclined boreholes. The fibre optic method should be used especially for long-term surveying the temperature field and its variations with time.

References

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