DISTRIBUTED FIBRE OPTIC TEMPERATURE SENSING: A NEW TOOL FOR LONG-TERM AND SHORT-TERM TEMPERATURE MONITORING IN BOREHOLES

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ABSTRACT

The Distributed Fibre Optic Temperature Sensing Technique (DTS) represents a new physical approach for temperature measurements in geosciences This method was applied for long-term surveying temperature variations with time caused by injecting and extracting hot water in a 600 m deep well The measuring system was installed as a permanent sensor in the annulus between casing and tubings The injectiodextraction regime was monitored by repeating the measurements every few weeks Short-term variations of the temperature during injection and extraction were studied by recording the temperature profile every 1 minute over a time period of several hours Testing shows that the fibre optic temperature sensing technique opens new possibilities for measuring the actual temperature along the entire length of a borehole as well as for monitoring short-term and long-term temperature variations

1. INTRODUCTION

Generally, the subsurface temperature is determined using a standard temperature sensor. For borehole measurements the sensor is installed in a logging device which is lowered as a moving probe into the open borehole with a given speed Despite the high temperature resolution, standard sensors have some significant limitations. For long-term or on-line temperature monitoring simultaneously the entire length of a borehole a great amount of single sensors would be needed which can not be economically realized. Also, in cases where the measuring medium is no more accessible standard temperature probes can not be used.

The distributed optical fibre sensing technique represents a new physical approach for temperature measurements. The basis of this method is described by Boiarski (1993), Dakin et al. (1985), Farries and Rogers (1984), Hartog and Gamble (1991), Hartog and Payne (1982), Rogers (1988, 1993).

First results on applications of fibre optic temperature sensing in boreholes as well as for long-term temperature monitoring for studying geotechnical and environmental problems (e g , waste deposits) are published by Heinemann-Glutsch et al. (1994), Hurtig et al. (1992; 1993; 1994), Hurtig and Schrotter (1993). From these results follows that fibre optic temperature sensing can be an efficient tool for temperature measurements in many application fields in geosciences. In this paper the capability of the method is studied for measuring short-term temperature variations during fluid-logging experiments as well as for long-term surveying the injection/extraction process in deep wells

2. FUNDAMENTALS OF THE DISTRIBUTED FIBRE OPTIC TEMPERATURE SENSING TECHNIQUE

The inelastic light scattering connected with a frequency shift of the scattered light is known as Raman effect The nature of this effect could be explained by the classical theory of electrodynamics.

Using the Raman effect the Distributed Optical Fibre Temperature Sensing (DTS) method was developed at the beginning of the eighties at Southampton University in England. It is based on optical time domain reflectometry (OTDR) (Rogers, 1988, Farries and Rogers, 1984, Hartog and Gamble, 1991) Principles and fundamentals of the used fibre optic measuring technique used are described by Hurtig et al. (1994) **A** pulsed laser **is** coupled to an optical fibre which is the sensing element. 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 Intensity and spectral composition of the backscattered light are determined by the molecules in the optical fibre. The backscattered light includes different spectral components whch are caused by differing interaction mechanisms between the propagating light pulse and the optical fibre. The Raman backscattering component is caused by thermally influenced molecular vibrations. Thus, its intensity depends on temperature. The Raman backscattered light has two components: the Stokes line and the Anti-Stokes line which have different intensities. The intensity of the Stokes line is only weakly depending on temperature, whereas the Anti-Stokes line shows is strongly depending on temperature

The basic principle of fibre optic temperature measurements thus consists in filtering the Stokes and the Anti-Stokes lines out of the backscattering light. Taking the ratio of the intensities of the Stokes and the Anti-Stokes lines external influences such as changes of the light source or of the optical fibre are eliminated.

The following relation holds.

$$I_a / I_s = \{(\kappa_0 + \kappa_k)^4 / (\kappa_0 - \kappa_k)^4\} \exp(-hc\kappa_k / kT) \qquad (1)$$

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

The intensities of both Raman lines are recorded with a time resolving power in the order of 10 ns. The temperature is determined as an integral value for a short section of the optical fibre and the space co-ordinate is determined from the traveltime of the propagating light pulse. Therefore, it is possible to measure the temperature simultaneously along the entire length of the fibre The space resolution is 1 m. This resolution can be increased by a two-fold or four-fold oversampling **As** the temperature values and their location along the optical fibre are simultaneously determined, an independent recording of the fibre length or distance (depth) using a standard borehole winch technique is not required.

The Raman backscattering intensity is integrated for a fibre section of a length of 1 m, 0.5 m or 0.25 m, respectively. Thus, the measured backscattering intensity defines the integral temperature for this interval in contrast to standard temperature sensors which give the local temperature at the location of the sensor. The number of measuring (distance) intervals can be high and depends only on the length of the optical cable (e.g., some km). Backscattering of light is a stochastic process, therefore, it is necessary to integrate the backscattering intensity for a given time interval. For a spatial resolution of 1 m an integration time of 1 min is sufficient to reduce the stochastic noise. The integration time must be increased by a factor of 2 or 4 if the space resolution is increased to 0.5m or 0.25 m, respectively, For a large fibre length (> 8 km) the optical absorption in the fibre decreases the available space and time resolution.

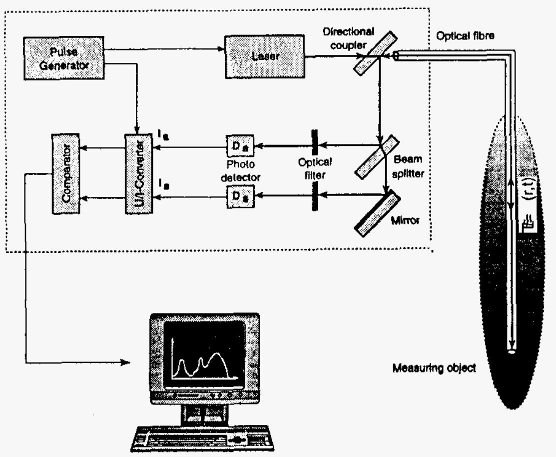

Fig. 1: Principle of Distributed Fibre Optic Temperature Sensing

From formula (1) follows that the absolute temperature is directly obtained from the intensity ratio of the Anti-Stokes and Stokes backscattering. Nevertheless, it is necessary to calibrate the used optical fibres because their temperature characteristics may vary depending on the specific material properties (geometry and chemical composition) and their temperature dependences. These properties can be different for different optical fibres. Therefore, the calibration hnction must be determined for the individual optical fibres before the measurements are performed using a laboratory temperature calibration equipment. The accuracy of the temperature measurements is 0.3K, and a resolution of <0 1 K can be reached. The available accuracy is controlled by the accuracy of the fibre-specific calibration hnction, whereas the available resolution and precision depend on the specific material properties of the used optical fibre. The device for fibre optic temperature measurements includes the transmitting and recording unit, a portable computer for controlling and data analysis, and the fibre optic cable (Figure 1). The optical fibre laser is neodymium-doped and has a wavelength of 1064 nm, the pulse duration is 10 ns. The directional coupler separates the backscattered light from the incident light pulse By means of beam splitter, optical filter, and photo detector the two Raman bands (Stokes [s] and Anti-Stokes [a] lines) are separated and their intensities are determined. Finally, the ratio of both intensities is calculated and transferred into temperature values using both the internal reference temperature of the equipment and the externally determined calibration hnction for the specific fibre type. The dimensions of the equipment are 450 x 320 x 340 mm and the total weight amounts to 20 kg.

The fibre optic cable used for the field experiments consisted of a plastic-coated high-grade steel tubule with 5 optical fibres and a total diameter of 7 mm

The fibre optic temperature sensing system operates without any electronic circuits along the fibre. Because the temperature is determined from the ratio of the two intensities of the Stokes and Anti-Stokes lines, age effects of the optical fibre can be neglected Thus, a long-term stability of the system is given.

In a monitoring well of a freezing shaft with very stable temperature conditions the fibre optic temperature sensing system was compared with results of a high precision borehole logging tool Figure 2 shows that both temperature curves fit well

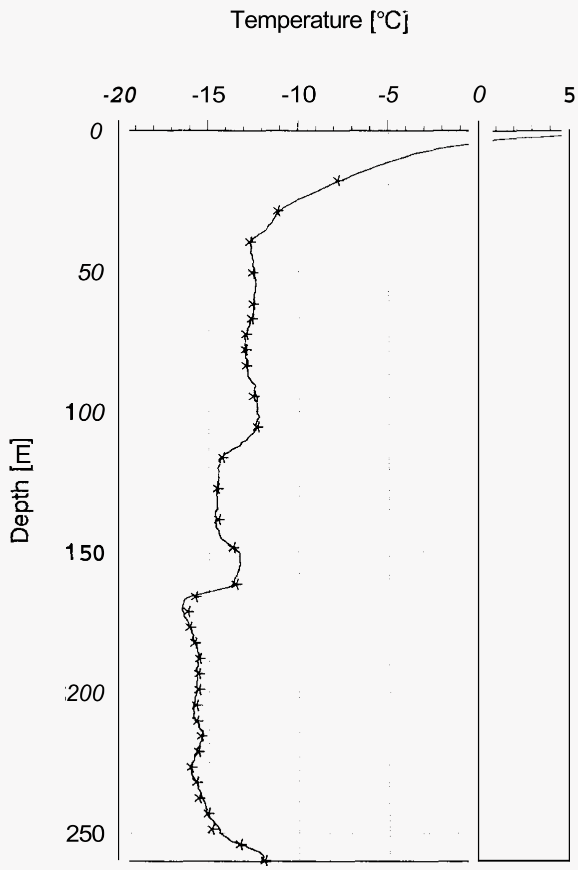

Fig.2: Fibre-optic (solid curve) and high resolution thermal logging (crosses) in a monitoring well of a freezing shaft

3. RESULTS

3.1 Fluid-logging experiments

Fluid-logging has advanced to a standard testing method for the hydraulic characterization of fractured rock. At the Grimsel rock laboratory (Switzerland), NAGRA initiated field experiments to study the applicability of fibre optic temperature sensing for fluid-logging (see Hurtig et al., 1994). The optical fibre was clamped to the injection tube and the borehole was shut in by a packer. The optical fibre was passed through the packer and the interval pressure was recorded by a pressure transducer. Subsequently, warm and cold water, respectively, was injected through the tubing to the bottom of the borehole and the temperature propagation along the hole was recorded by the fibre optic measuring system. Injection and extraction flowrates were continuously monitored .

The experiments were performed in inclined boreholes under different hydraulic and thermal conditions. The boreholes penetrate crystalline rock, the measuring length was 40 m.
The fluid-logging experiment included the phases of warm water injection and free outflow. A pressure level of 2 95 bar was obtained for a mean flowrate of 8 5 Ymin (injection) and 1 5 l/min (extraction). At this pressure level warm water (28°C) was injected (Figure 3a). For free outflow of the water the temperature was recorded until the equilibrium temperature was obtained (Figure 3b) At a depth of 17 - 18 m the temperature strongly decreases. The warm water front breaks down sharply indicating a fracture zone with a high transmissivity. Other open fracture zones are indicated at a depth of 5 m, 23m, and 32-33 m.
The results gained by the fluid-logging experiments fit well to the findings from core analysis, geophysical logging and packer testing.

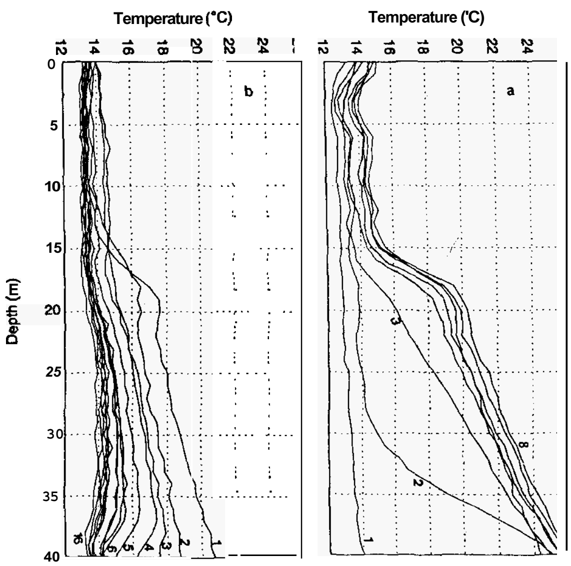

Fig 3 Fluid-logging experiment warm water injection (a) and free outflow (b) Numbers indicate sequence of records (time interval 10 min)

3.2 Long-term surveying of water injection/extraction in boreholes

Re-injection of fluids in boreholes is connected with temperature variations. The injection process can be surveyed by monitoring the temperature. Furthermore, from temperature variations in monitoring wells around re-injection boreholes the breakthrough of the thermal front and hydraulic connections between re-injection and monitoring well can be identified.
Fig. 4 shows the results of temperature measurements in a 600 m deep re-injection well in 1993 (30.7, 25.8. 20.9., 7.10., 27.10., and 22.11.). The fibre optic sensing cable was permanently installed in the narrow annulus between the casing and the tubing The annulus was water-filled. The strong increase of temperature at a depth of about 20 m is due to the fluid level in the annulus. The temperature curve for August 25 shows a strong distortion of the temperature field due to the temperature of the injected fluid. Since October 7 there has been no injection, thus the equlibrium temperature has been re-established The typical course of the temperature profile depending on the different heat conductivity values of the geological formation is obtained when the equilibrium temperature is reached.

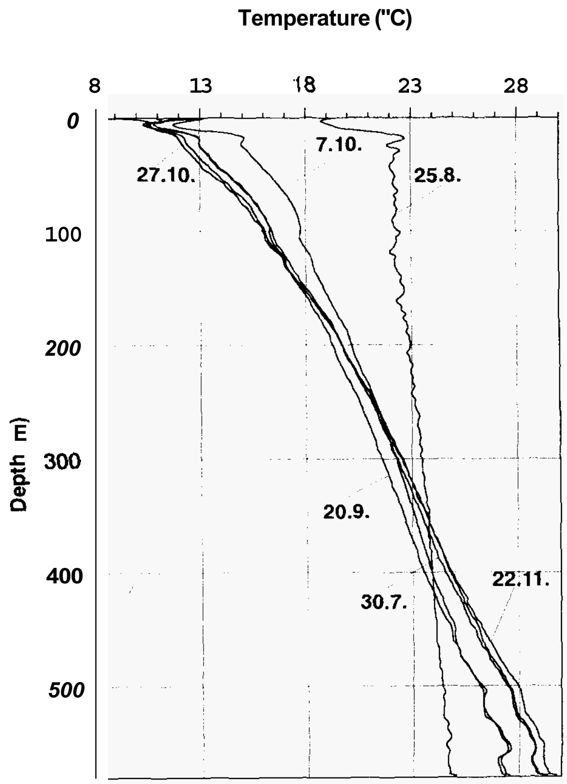

Fig 4 Fibre optic temperature measurements in the annulus of an injection well in 1993 (the labels give the measuring date of the individual curves)

4. CONCLUSION

The measurements show 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 standard borehole probes can not be used. The system can be installed also in horizontal and inclined boreholes. The fibre optic temperature sensing should be used especially for on-line and long-term surveying the temperature field and its variations with time rather than for simple borehole logging.

REFERENCES

Boiarski, A. A (1993). Distributed Fiber Optic Temperature Sensing. In: ***Applications of Fiber Opttc Sensors in Engineering Mechanics,*** F. Ansari (Ed). American Society of Civil Engineers, New York, pp. 210-224.

Dakin, J P , Pratt, D.J., Bibby, G W. and Ross, J.N. (1985) Distributed optical fiber Raman temperature sensor using a semiconductor light source and detector. ***Electronic Letters,*** Vol. 21, pp. 569-570.

Farries, M.C. and Rogers, A.J. (1984). Distributed Sensing Using Stimulated Raman Action in a Monomode Optical Fibre. Proc 2nd Int Conf on Optical - fibre Sensors, Stuttgart, pp. 121-132.

Hartog, A. and Payne, D.N. (1982). Fiber optic temperature distribution sensor. Proc. IEE Colloq. on Optical Fiber Sensors (London).

Heinemann-Glutsch, B., Hurtig, E and Marschall, P. (1994) Fluid logging with fixed probe arrays. In. ***Developments in Hydrotesting, Fluid Logging and Combined Salt/Heat Tracerexperiments in the BK site (Phase III),*** P. Marschall and S. Vomvris (Eds). NTB 93-47, Nagra Technical Report, Wettingen, Switzerland, pp. 18-45.

Hurtig, E. and Schrotter, J. (1993). Fibre optic temperature measurements in deep boreholes. KTB Report 93-2, pp 377-380

Hurtig, E , Schrotter, J., Großwig, S., Kühn, K., Harjes, B and Wieferig,W. (1992). Temperaturmessungen in Bohrlochern mit Hilfe optischer Fasem. In: Forum fir Zukunftsenergien e.V Geothermische Vereinigung e.V , Geothermische Fachtagung 1992, Tagungsband, Bonn, pp. 311-324.

Hurtig, E., Schrotter, J., Großwig, S., Kiihn, K., Harjes, B., Wieferig, W. and Orrell, R.P. (1993). Borehole Temperature Measurements using Distributed Fibre Optic Sensing. ***Scientific Drilling,*** Vol. 3(6), pp. 283-286.

Hurtig, E., Großwig, S., Jobmann, M., Kiihn, K. and Marschall, P. (1994). Fibre Optic Temperature Measurements in Boreholes. Application for Fluid Logging. ***Geothermics,*** **Vol**. 23 **(4),** pp. 355-364.

Rogers, A.J. (1988). Distributed Optical-fibre Sensors for the Measurements of Pressure, Strain and Temperature. ***Phys. Rep.,*** Vol.169, pp. 99-143.

Rogers, A.J. (1993). New Methods for Distributed Optical-Fibre Measurement of Strain and Temperature in Large Structures In. ***Applications of Fiber Optic Sensors in Engineering Mechanics,*** F. Ansari (Ed). American Society of Civil Engineers, New York, pp. 225-235