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TEMPERATURE LOGGING BY THE DISTRIBUTED TEMPERATURE SENSING TECHNIQUE DURING INJECTION TESTS

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ABSTRACT

The Distributed Temperature Sensing (DTS) technique using an optical fiber sensor is a relatively new method in temperature logging. Using the Optical Time Domain Refractometry (OTDR) technique and temperature dependency of the Raman backscattering light, it is possible to measure the temperature along the entire length of the optical fiber at an interval of ca. 1m at a time. Because it is not necessary to move point sensor during measurement, the DTS technique enables us to make simultaneous monitoring of the temperature profile of the well at a time interval of a few to several minutes. This feature of the DTS temperature logging system is suitable for detecting temporal change of the temperature profile of a geothermal well such as during injection and production tests. Recently, we introduced a new optical fiber sensor combined with a capillary tube, and are able to measure the temperature profile and pressure at the end of the sensor simultaneously. The major results of field experiments during injection tests at the Sumikawa geothermal area, northeast Japan, and the Sugawara geothermal area, southweat Japan, are as follows.
1. Locations of fractures can be detected clearly by the temporal change of the temperature. Fractures are more clearly detected during injection than recovery.. The DTS logging can show the fracture locations more clearly and easily than conventional temperature logging systems.
2. The water level can be traced by the DTS logging. The pressure profile of a borehole can be calculated from the water level and the temperature profile data.
3. Comparison between the calculated pressure value from temperature profile and the measured pressure value suggests that it may be possible to evaluate the amount or rate of inflow into the borehole from the reservoir.. To ensure this comparison is valid, precise calibration of the single-ended fiber sensor is required.

1. INTRODUCTION

Recently, the Distributed Temperature Sensing (DTS) technique has been attracting a considerable attention in geophysical and geothermal fields as a new temperature logging technique (e.g., Hurtig *et al*., 1993; Osato *et al*., 1995; Sakaguchi and Matsushima, 1995; Benoit and Thompson, 1998; Wisian *et al*., 1998).

The DTS technique has an advantage over a conventional point probing logging system in that it enables us to make simultaneous monitoring of the temperature profile of the well at a time interval of a few to several minutes. This feature is suitable for detecting temporal changes in the temperature profile of a geothermal well such as during temperature recovering after drilling, injection tests and production tests. Here we report the results of field experiments of measurements during cold water injection tests in three geothermal wells and show some advantages of the DTS temperature logging system.

2. PRINCIPLES AND EQUIPMENT

2.1 Principles

The key technique is optical time domain reflectometry (OTDR). A laser pulse is launched into an optical fiber. As the pulse passes through the fiber, energy is lost owing to scattering. The intensity of the backscattered light decays exponentially with time, given uniform losses within the fiber. Therefore, knowing the speed of the light in the fiber, it is possible to convert this intensity against distance. Among the scattered light components, Raman scattering due to molecular vibrations is temperature sensitive. Raman scattering signal is split into two "bands" displaced approximately symmetrically about the incident wavelength: the Stokes band and the Anti-Stokes band . The intensity of the Stokes band is only little temperature sensitive, whereas the intensity of Anti-Stokes band is strongly temperature dependent. The temperature of the fiber is expressed by following relation:

$$\frac{\mathrm{I}_a}{\mathrm{I}_s} = \frac{(\bar{\gamma}_0 + \bar{\gamma}_k)^4}{(\bar{\gamma}_0 - \bar{\gamma}_k)^4} \exp\left(\frac{-h\ c\ \bar{\gamma}_k}{\mathrm{KT}}\right) \qquad (1)$$

where
I_a : intensity of the Anti - Stokes band
I_s : intensity of the Stokes band
$\bar{\gamma}_0$: wavenumber of the incident light
$\bar{\gamma}_k$: shift amount of the wavenumber
T : temperature (K)
K : Boltzman' s constant
h : Plank' s constant
c : light velocity

Using OTDR technique and temperature dependency of the Raman backscattering light, it is possible to measure the temperature along the entire length of the optical fiber. In actual measurement, signals must be stacked (or averaged) for several tens of seconds to several minutes because the intensity of the Raman scattering is very weak.

2.2 Equipment

The DTS temperature logging system (YORK DTS-80) consists of a transmitting and data processing unit, a personal computer for control and data storage, and an optical fiber sensor. DTS-80's depth precision is 1.027m.

We used two kinds of optical fiber sensor. One is a looped optical fiber sensor manufactured by Nippon Steel Welding Products & Engineering Co. Ltd. Two strings of optical fiber are contained in a SUS tube of 2.4mm O.D., and they are connected at the bottom end of the sensor cable to make a loop. It measures only temperature distribution. The other is a single-ended optical fiber sensor combined with capillary tube produced by Pruett Industries International. Both the optical fiber and capillary tube are inserted in a SUS tube of 6.4mm O.D. The surface end of the capillary tube is separated from the optical fiber and connected to a pressure transducer. This sensor measures the bottom-hole pressure as well as temperature distribution, but needs more careful calibration than a looped sensor.

3. FIELD EXPERIMENTS

We undertook three field experiments. Two were at the Sumikawa geothermal filed, Akita, northeast Japan, and the other at the Sugawara geothermal field, Oita, southwest Japan. The experiment specifications are listed in Table 1.

The looped optical fiber sensor was used in the experiment at the well SN-8R of the Sumikawa field. The single-ended fiber sensor combined with capillary tube was used in the experiments at the well KY-1, Sumikawa field and the well BS-6, Sugawara field. Water table depth was measured by the Echometer in KY-1 and BS-6 experiments.

We picked up some interesting results from the temperature logging by the DTS system and show them in the following sections. A detailed report of each experiment is being prepared for publication.

4. RESULTS

4.1 Detection of fracture locations

Fig. 1 shows the temporal change of the temperature profile of well SN-8R in the Sumikawa field during an injection test. Step-like bends, A-F in Fig.1 (a), indicate the outflow points of the water from the borehole, that is fractures. To be exact, slotted casing may affect the temperature profile curves. Of course, these kind of bends are also commonly observed in conventional temperature logging charts. However, repeated measurements by the DTS logging system provide clearer evidence as shown in Fig.1 (a).

During the temperature recovery period shown in Fig.1 (b), the bends are not so clear as during injection. It is rather difficult to find fracture points from a single temperature profile curve. But it is possible to obtain the location of the fractures from a series of DTS temperature profile curves.

Comparison between the temperature profile curves of the injection period and those of the recovery period provides the information on fracture locations.

The methods used to detect the location of fractures by the DTS logging data are the same as those of conventional temperature logging. However, the DTS logging can offer clearer data more easily.

4.2 Detection and trace of the water level

The water level is a valuable parameter in analyzing geothermal well and reservoir behavior. The DTS logging system can detect and trace the water level at small time intervals.

Fig.2 shows temperature profiles around the water table of the well KY-1, Sumikawa field, just after 62.5 hour injection. The water level was detected as a sharp bend of the temperature profile curve. The DTS cannot detect the water table during injection because cold water follows the sensor tube. However, the water level was detected about 10 minutes after injection stopped (62.67 hour curve in Fig.2). KY-1 has a rather small permeability. Thus, the water level kept going down slowly after injection ceased.

A steam layer began to grow after about 65 hour. The growth of the steam layer was clearly detected by the DTS temperature profiles. An Echometer, which sounds the water level by the traveling time of a sonic wave exploded at the well head, could not obtain a reflected wave record because of the steam layer.

At the other two experiments at SN-8R and BS-6, the water level was detected by the DTS temperature profiles (Figs.1 and 3).

4.3 Calculation of the pressure profile

Once the water level and temperature profile are obtained, the pressure profile of a borehole can be calculated by integrating the weight of the water column of a given temperature profile. A static condition is assumed in this calculation. If the bottom-hole condition is not static, i.e. there is inflow or outflow of a certain amount, then the calculated pressure may differ from true pressure.

Figs.3 and 4 show an example at the well BS-6, Sugawara field. At BS-6 experiment, we used a single-ended fiber sensor combined with capillary tube. We obtained both temperature profile data and bottom-hole pressure data at the same time. BS-6 has a high permeability and the water level change after injection stop is quite different from that of KY-1(Fig.2). A rapid temperature recovery at the bottom (Fig.3) and rising water level (Fig.4b) immediately after injection stopped suggest an inflow of hot water into the borehole from the surrounding formations.

Calculated and observed pressures are shown in Fig.3c. The difference between the two is 0.08 MPa immediately after injection stopped and about 0.06 MPa after 70 hours. The higher observed pressure compared with the calculated pressure supports our hypothesis of inflow into the drill hole. But it may be unlikely that there is still a pressure difference of 0.06 MPa after 120 hours. This may be due to incomplete calibration of the single-ended optical fiber.

5. CONCLUSIONS

Results of three field experiments of the DTS temperature logging system yielded some interesting results.

Locations of fractures can be detected clearly by the temporal change of the temperature. Fractures are more clearly detected during injection than recovery periods. The DTS logging can show the fracture locations more clearly and easily than conventional temperature logging systems.

The water level can be traced by the DTS logging. The pressure profile of a borehole can be calculated from the water level and the temperature profile data.

Comparison between the pressure values calculated from temperature profiles and measured pressure values suggests that it may be possible to evaluate the amount or rate of inflow into the borehole from the reservoir. To ensure this comparison is valid, precise calibration of the single-ended fiber sensor is required.

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Table 1. Specifications of the field experiments

Well	SN-8R	KY-1	BS-6
Location	Sumikawa, NE Japan	Sumikawa , NE Japan	Sugawara, SW Japan
Well depth	1440 m	1604 m	611 m
Maximum temperature	219 °C	200 °C	205 °C
Experiment date	Oct. 28 – Nov. 2, 1994	Oct. 15 – 21, 1997	Mar. 12 – 18, 1996
Sensor	Looped fiber	Single-ended fiber + capillary tube	Single-ended fiber + capillary tube
Sensor depth	1370 m	1590 m	583 m
Injection duration	16.5 hours	24 hours	5.5 hours
Injection volume	420 m^3	29 m^3	751 m^3
Recovery duration	95 hours	71 hours	116.5 hours
Water level measurement	No	Yes (Echometer)	Yes (Echometer)

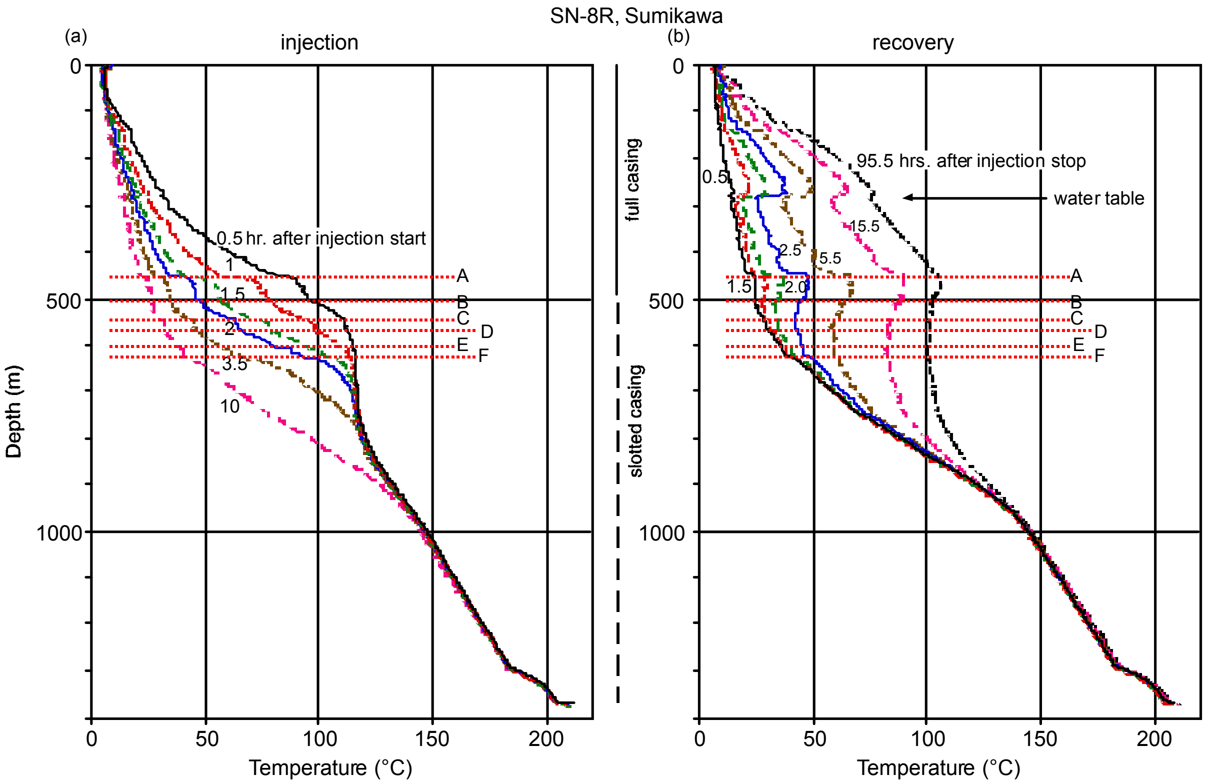

Fig.1. Temporal change of the temperature profile of the well SN-8R, Sumikawa field
(a) during water injection, (b) after injection stop. A - F: infered fracture location.

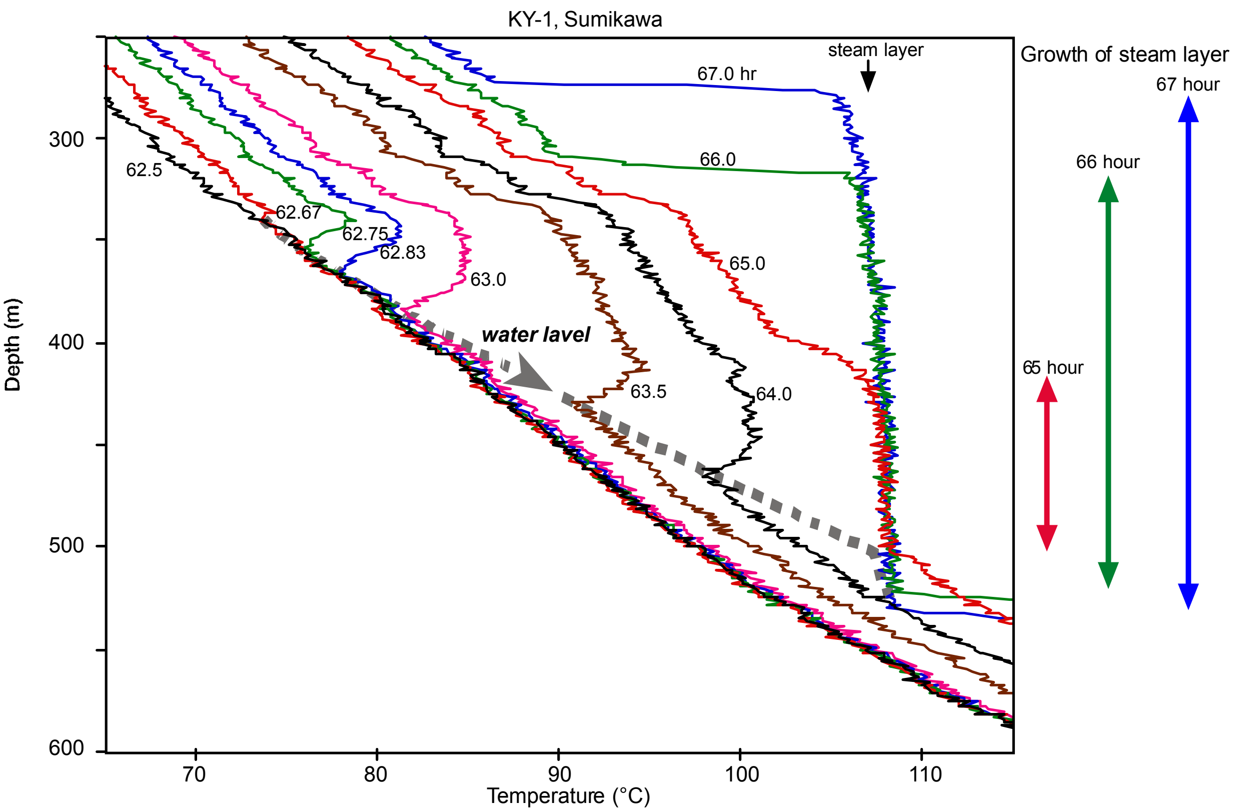

Fig.2. Temporal change of the temperature profile aroud the water level in the well KY-1, Sumikawa field

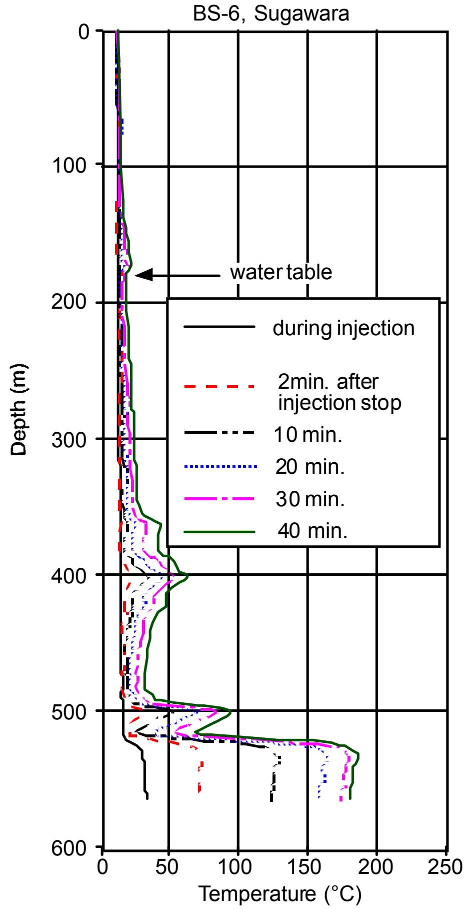

Fig. 3. Temporal change of the temperature profile of the well BS-6, Sugawara field, after injection stop

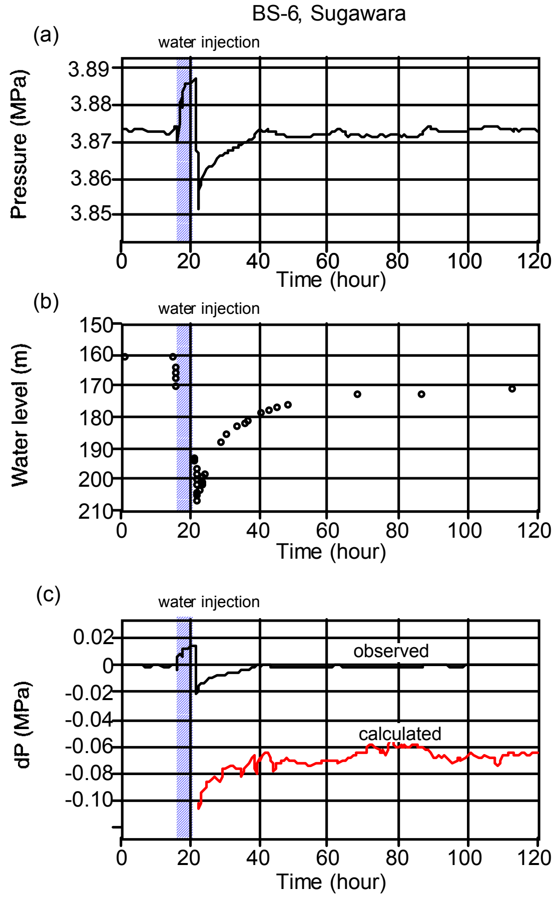

Fig. 4. Bottomhole pressure measured by capillary tube (a), water level maesured by Echometer (b), and comparison between obseved and calculated bottomhole pressure values (c). dP is the difference from the initial pressure value.