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DELINEATION OF FRACTURED RESERVOIR BY TRANSIENT TEMPERATURE ANALYSIS USING FIBER OPTIC SENSOR

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ABSTRACT

One of the novel applications for the fiber optic sensor is to acquire instantaneous distributed temperature along the cable. The measurement mechanism is based on Raman back scattering whose intensity is sensitive to temperature. The advantage of instantaneous acquisition of distributed temperature over the entire borehole is manifold. The obvious one is to be able to measure transient temperature phenomena better. For example, temperature recovery test has been routinely conducted by a few temperature logging runs whilst each run separated by certain time intervals. Regardless of the model used to derive geostatic temperature, only a few points on the plot are available. With temperature profile over the entire borehole with sampling rate of 1 minute or so, the fiber optic temperature logging enables us to optimize the time required to determine whether the plot fits to the model.

The unique feature of the fiber optic distributed temperature sensor can be used as fluid flow logging which is to obtain velocity profile whilst injecting water into fractured type highly productive well. As water is injected into borehole, the fluid column is pushed downwards. Since the flow in such a condition behaves mostly as plug flow, temperature profile should move at the same velocity as the fluid flow. In other words the change of temperature profile should yield the fluid flow profile. The fluid flow seen by the temperature profile change is best detected by the movement of a fluid boundary showing high temperature contrast such as the one between cool injected water and hot geothermal water or other area where sharp temperature contrast is present regardless its cause. The velocity profile is used to analyze fluid entry and their flowrates. The velocity detection is so sensitive that it may be possible to derive borehole diameter if the fluid velocity profile deeper in the hole shows no fluid loss into formation above. If it is conducted at the end of temperature recovery test, it could yield information otherwise requiring temperature log, flowmeter log and caliper log.

1. INTRODUCTION

The fiber optic distributed temperature sensor is based on Raman back scattering and OTDR (optical time domain reflectrometry). Raman scattering has an intensity order typically less than 10^{-6} of the incident ray and its frequency different from the incident ray. The phenomenon is predicted by quantum physics. It consists of two types of wave length, one has wavelength longer than the incident ray (Stokes scattering) and the other has shorter wavelength (anti-Stokes scattering). Intensity of both Stokes and anti-Stokes are sensitive to temperature. However the intensity of anti-Stokes is more sensitive to temperature than that of Stokes. The relationship may be described as follows.

$$P_S = P_0 \cdot K_S \cdot \Psi_S(t)$$

$$P_A = P_0 \cdot K_A \cdot \Psi_A(t)$$

$$\Psi_S(t) = \left\{ 1 + \frac{1}{\exp\left(\frac{hc\nu}{kt}\right) - 1} \right\} \Bigg/ \left\{ 1 + \frac{1}{\exp\left(\frac{hc\nu}{kt_0}\right) - 1} \right\}$$

$$\Psi_A(t) = \left\{ \frac{1}{\exp\left(\frac{hc\nu}{kt}\right) - 1} \right\} \Bigg/ \left\{ \frac{1}{\exp\left(\frac{hc\nu}{kt_0}\right) - 1} \right\}$$

where P_O, P_S,and P_A are intensities of incident ray, Stokes and anti-Stokes. K_S and K_A are coefficients specific to the fiber chracteristics for Stokes and anti-Stokes. h is Planck's constant. c is speed of light. ν is frequency of the incident ray. k is Boltzman constant. t is temperature at the occurrence of scattering. t_0 is reference temperature. Raman scattering occurs at all places along the optical fiber and reflects the fiber temperature at the occurrence. The signal is processed using OTDR technique to depict depth information.

There have been already certain number of case studies reported on the fiber optic temperature sensors (Matsushima et al.,1996, Grosswig et al.,1997, Forster et al.,1997). Wisan et al. (1998) reported it could work up to 750ºC depending on the configuration. Karaman et al. (1996) introduced a system combined with Raman back scattering based temperature sensor and interferometry based pressure sensor. Meggitt (1995) further explored high precision interferometry sensor to be used in various applications. All of them feature the fiber optics distributed sensing capability which are unique compared with the conventional logging methods. The advantage of distributed temperature sensing is to be able to monitor rapid change of temperature in the borehole as it occurs during production, injection or temperature recovery. The main objective of our study is to explore application of distributed temperature logging in geothermal development.

The fiber optic temperature sensor used in this study is the advanced version of the one earlier developed by Watanabe et al. (1993) and Kitakoga et al. (1995). It is designed with robust mechanism against hydrogen and hydroxyl absorption, which is a known weakness of the optical fiber(Ohnishi et al., 1986). In the typical mode of measurement, temperature profile at the depth interval of every meter where each temperature is averaged over 3 meters at the depth. The entire temperature profile can be updated at the sampling rate of about 1 minute. It can work up to 3km of borehole and up to 350ºC within 1ºC precision.

2. TEMPERATURE RECOVERY TEST

Up to now, the geostatic temperature of geothermal well is best estimated by temperature recovery test, which consists of several runs of temperature logs with certain time intervals run after drilling circulation is stopped. The geostatic temperature at specific depth could be estimated by plotting temperatures obtained by a suite of logs(Dowdle and Cobb, 1975) if conductive heat flow is assumed without any fluid movement. Regardless of the theoretical model used to derive the geostatic temperature, more the points available on the plot, easier the prediction of the trend will be if the model assumed is right. With the conventional logging, we may not be able to afford even to determine if the data points are sufficient as it probably involves unacceptable number of logging runs.

The fiber optic temperature sensor allows a break through as it provides temperature profile of the borehole at sampling rate as low as 1 minute or so. Fig.1 through Fig.4 illustrate the advantage of the fiber optic sensor for a temperature recovery test. In the test, water at 13 degree Celsius was injected into a geothermal well at rate of 200 litre per minute for one hour. Then temperature recovery was monitored for a little less than 2 hours. During the entire test, temperature profile in the cased hole section was monitored by the fiber optic temperature sensor.

The computed result using the Horner function matches well with the original geostatic temperature above water level at about 530m and over the hot water section with monotonic temperature change. It however does not match so well in vicinity of water level and the region with abrupt temperature change. As a matter of fact it should have been tested longer as Fig.3 of Horner plot suggests. But what is important here is that with the real time temperature data we are able to decide when to call off test and evaluate the quality of the model.

3. FLUID LOGGING

Earlier work by Hurtig et al. (1994, 1996) a showed possible application of the fiber optic temperature sensor for fluid logging. Takeuchi (1996) demonstrated that a temperature logging device with multiple thermister sensors would yield very useful information when analyzing shallow permeable water bearing formation. Both recognized the importance and the usefulness of sensing dynamic temperature behavior caused by fluid movement in the borehole.

We further developed the idea to apply the fiber optic temperature sensor for analyzing fluid velocity profile in the borehole, which is a similar product as given in the conventional spinner flowmeter survey. It is designed to obtain flow velocity profile whilst injecting water into fractured highly productive wells. The measurement principle is that water injection into a borehole pushes the fluid column downwards, thus it causes temperature profile to move at the same velocity as the fluid flow. By analyzing temperature profile development over the time, we should be able to obtain fluid flow profile. The fluid flow monitored by temperature profile is best detected by the movement of the fluid boundary showing high temperature contrast, such as the one between injected water and geothermal hot water. In a way, it may be similar to R/A tracer log while being able to access the entire profile every 1 minute or so. The flow velocity profile is used to analyze fluid entry points and their flowrates.

Fig.5 illustrates temperature profile development whilst injecting water into a re-injection well at rate of a little more than 200 litre per minute. Even at a glance, one may be able to see temperature profile curves with large spacing from surface down to 200m, then followed by those with regular spacing down to about 400m, then followed by those with successively condensed spacing. These features are roughly explained as that the change from large spacing to regular one corresponds to the water level at 205m, the regular spacing corresponds to a lack of fluid entry points and successive packed spacing should correspond to location of fluid entry into the formation.

The usual curve correlation processing over the movement of the temperature boundaries should yield more precise analysis of the fluid velocity profile. The computation result applying curve correlation technique is shown in Fig. 7. It clearly confirms earlier rough estimation of the raw data. An interesting phenomena is seen along the fluid entry region during on the recovery as temperature continued decreasing even if the geostatic temperature is higher than the temperature at the time. This seemingly confusing phenomena may be explained by cooling effect extending deeper into the surrounding formation because of cool water entry. It should also be noted that the fiber in the hole is likely to be seated on the borehole wall, where temperature is higher than at the hole center. As shown in this example, in order to fully understand the actual temperature phenomena in the well, we must take into account not only the conductive heat flow but also the heat flow associated with the mass flow, probably with consideration of complex boundary conditions. Although numerical simulations may offer a solution to such problems, it will need good temperature data such as those obtained by the fiber optic temperature log.

Over the interval between 200m and 400m, one may notice that fluid flow velocity varies with the mid-rate at 6 meter per minute. With this flow velocity pattern, it is more natural to expect that this flow velocity variation is not caused by fluid entry into the formation. Rather it makes more sense that it is caused by change of borehole diameter if no fluid loss into formation is assumed.
Although it is not shown here, the conventional spinner flowmeter was run after our test run. The spinner result very well agreed with our result on the fluid entry point. An advantage is that the required injection flowrate was only a fraction of what was required for the conventional spinner type flowmeter. Even with the large injection rate used, the conventional spinner flowmeter barely managed to show flow velocity variation caused by possible borehole diameter change.

4. CONCLUSION

We have developed new logging methods using the fiber optic temperature sensor featuring dynamic temperature profile measurement. One is to improve and optimize temperature recovery test. The other one is the fluid flow logging which is used to detect and evaluate fluid entry as well as to derive borehole diameter. This fluid flow log can be conducted at the end of temperature recovery test, thus yielding all the information otherwise requiring temperature log, flowmeter log and caliper log.

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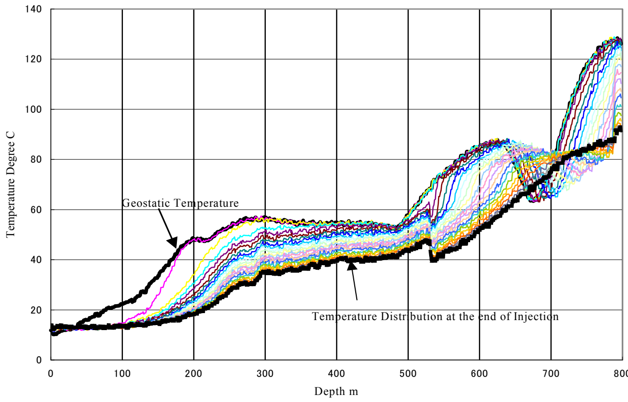

Figure 1. Temperature profile during water injection. 9-5/8” casing shoe at 799m. Slotted liner from 797m to 1101m

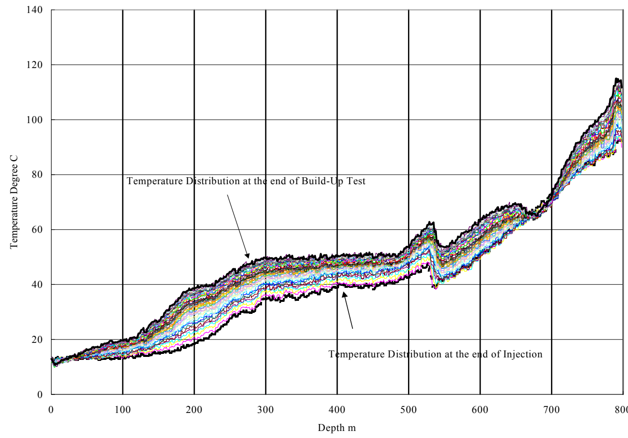

Figure 2. Temperature profile during temperature recovery.

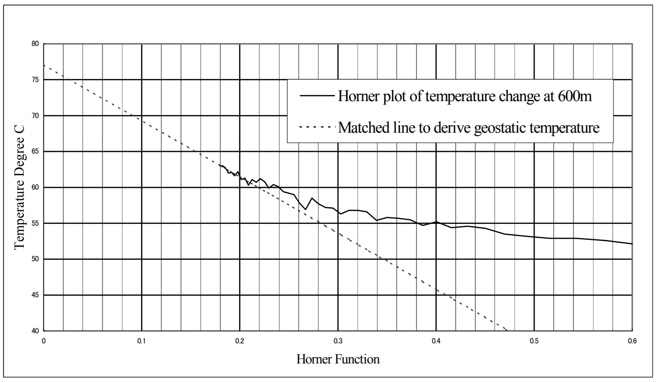

Figure 3. Horner plot of temperature data at 600m from the above well during temperature recovery test.

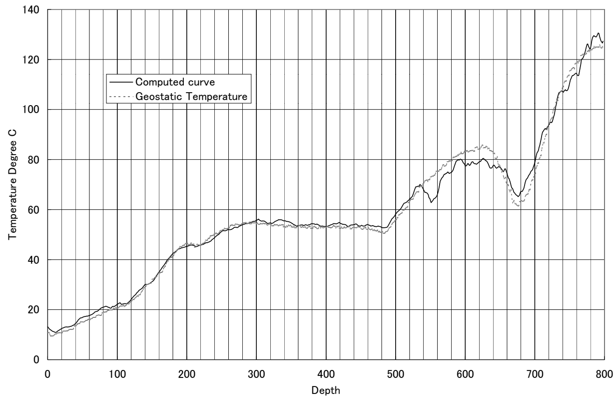

Figure 4. Computed geostatic temperature in comparison with the actual one.

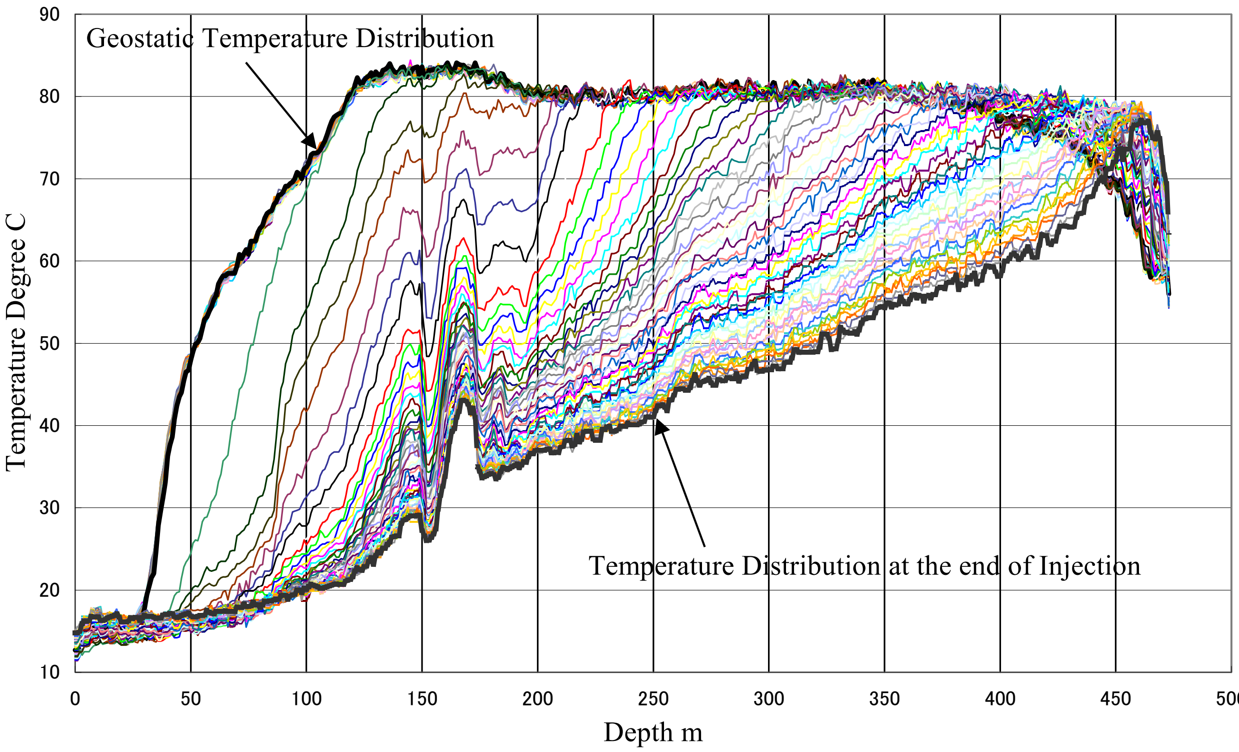

Figure 5. Temperature profile of Well B during water injection. 14-3/4" casing shoe at 149m. 11-3/4" slotted liner from 149m to T.D.

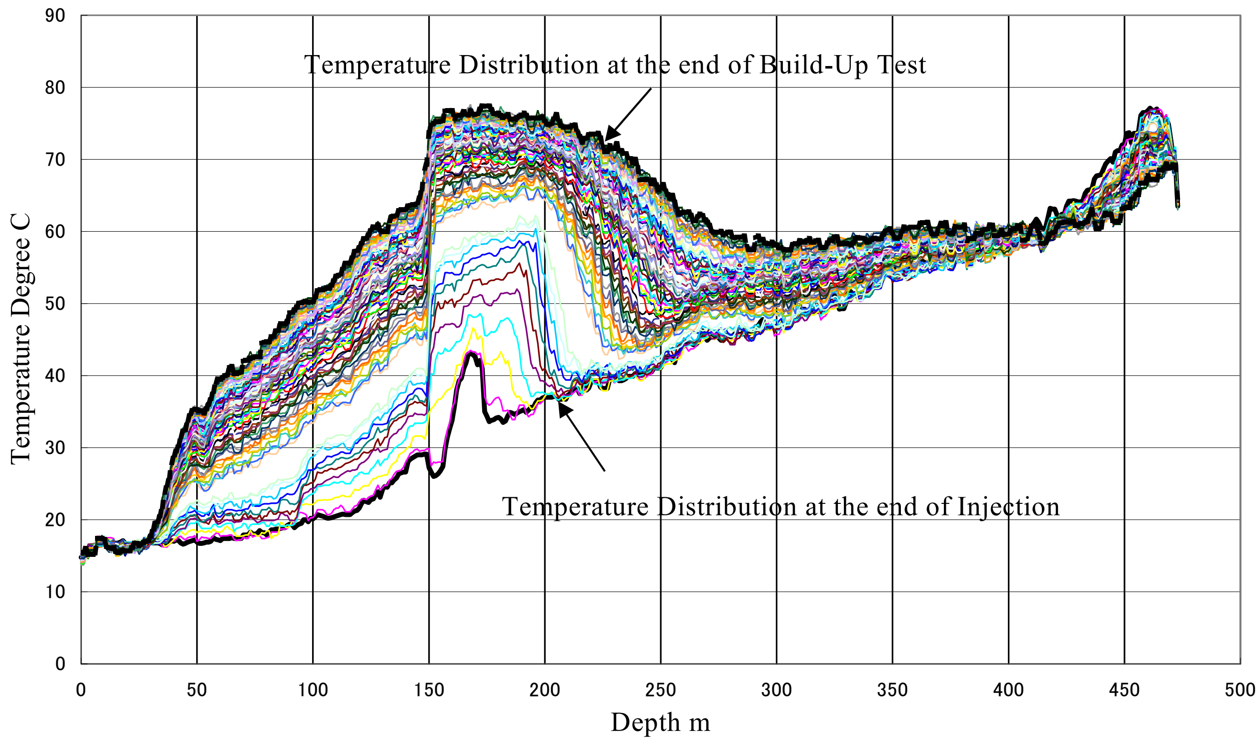

Figure 6. Temperature profile of Well B during temperature recovery.

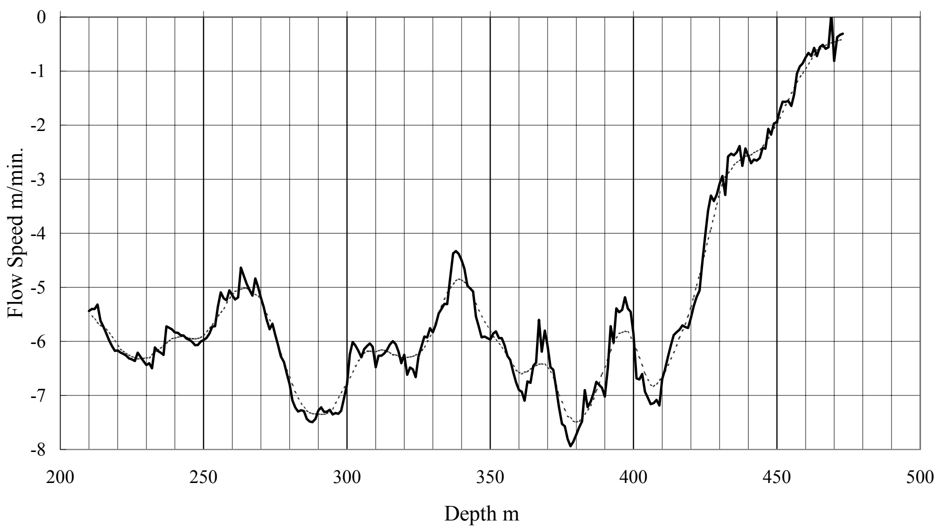

Figure 7. Fluid flow velocity profile of Well B during water injection computed from the temperature profile.
Solid line shows the raw velocity. Dotted line shows averaged one.