MEASUREMENT OF THE IN *SITU* THERMAL CONDUCTIVITY OF FORMATIONS IN A GEOTHERMAL FIELD - METHOD AND RESULTS OF MEASUREMENT -

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Key Words : Downhole Coaxial Heat Exchanger, geophysical techniques, Hawaiian basalt, heat flow, *in situ* thermal conductivity

ABSTRAC'I'

In order to estimate thermal outputs of downhole heat exchangers or, in geophysics, to determine heat flows in the earth's crust more accurately, it is necessary to know the *in situ* thermal conductivities or effective thermal conductivities of formations. The authors have been proposing the Downhole Coaxial Heat Exchanger (DCHE) as a geothermal energy extraction method and carried out a field experiment with the DCHE in 1991 on the island of Hawaii using the HGP-A well. The formation surrounding the well consists only of basaltic rock. One of the purposes of the experiment was to investigate the *in situ* heat transfer characteristics of the formation. As a result, the heat transfer mechanism in the measurement interval was identified as almost pure conduction and the thermal conductivity corresponding to the interval was estimated to be 1.6 W/m·K. The estimated heat transfer mechanism and the thermal conductivity were concordant with the mechanism inferred from measured temperature distributions in the well and the thermal conductivity of Hawaiian basalt, respectively. Also, possible error associated with the estimated thermal conductivity was inferred to be within a range of - 0.1 to + 0.2 W/m·K. This indicates that measurements using the DCHE as an *in situ* thermal conductivity measurement probe are quite practical.

1. INTRODUCTION

There are several types of potential or as yet undeveloped geothemial resources including Hot Wet Rock (low productivity convective formations), Super Hot Rock, magma origin fluid systems (volcanic geothermal reservoirs and magmatic fluid reservoirs) and magma. The authors have been proposing the Downhole Coaxial Heat Exchanger (DCHE, see Fig. 1) as a heat extraction method for the above mentioned resources and studying it assuming Hot Wet Rock as the first target.

As for the direct use of geothermal energy, other types of downhole heat exchangers such as the U tube heat exchanger and the conventional type coaxial heat exchanger have been used widely to extract heat from shallow and low temperature formations for the space heating of houses or buildings (e.g., Morgensen, 1986; National Geothermal Association *et al.*, 1990; Rybach *et al.*, 1992). In order to estimate the thermal outputs of these heat exchangers accurately, it is essential to know the *in situ* heat transfer performance of formations.

On the other hand, in geophysics, it is necessary to know the *in situ* thermal conductivity or effective thermal conductivity (hereinafter, these conductivities shall be simply called thermal conductivities) to calculate heat flows in the earth's crust. Because of the difficulty of measuring *in situ* thermal conductivity, the measured thermal conductivities of core samples are commonly used to estimate heat flows. In such cases, there is a possibility of there being significant errors in the determined values when formations are complex or when there is natural convection in the fonnations. Thus, it is necessary to measure the *in situ* thermal conductivities of formations to detemiine the heat flow accurately.

However, except for the measured *in situ* thermal conductivities of shallow or short intervals (e.g., Poppendiek *etal.*, 1982), it is difficult to find measured values of deep or comparatively long intervals. This seems to be due to the lack of a practical or convenient measurement method for *in situ* thermal conductivity of formations under such conditions.

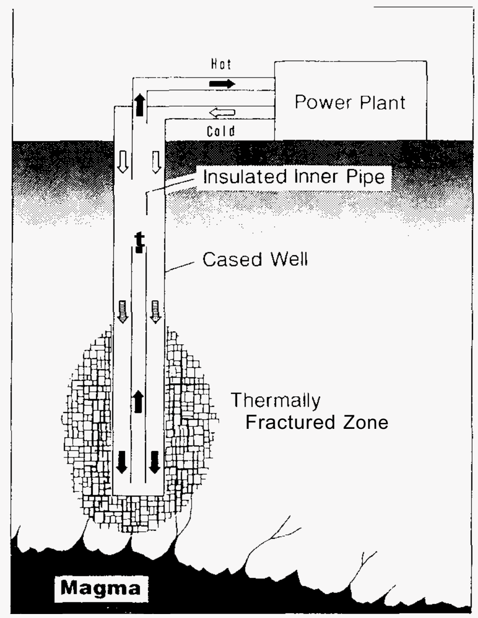


Fig. 1 Concept of the Downhole Coaxial Heat Exchanger (DCHE).

In 1991, the authors carried out a field experiment of the DCHE on the Island of Hawaii at the HGP-A well (Morita *et al.*, 1992 a, b). One purpose of the experiment was to investigate or measure the *in situ* heat transfer characteristics of the fommtion. The analysis of the experimental data indicated that the DCHE can also be used as an accurate probe for *in situ* thermal conductivity measurements.

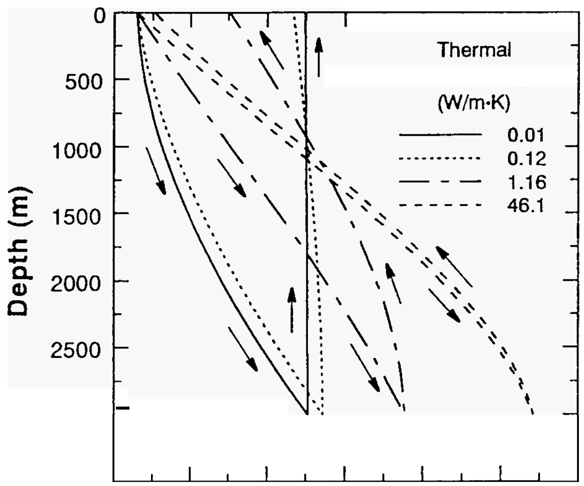
In this paper, the authors report the method for the *in situ* thermal conductivity measurement with the DCHE and the results of the measurement of the thermal conductivity of the formation.

2. THE DCHE AND THE MEASUREMENT METHOD

The DCHE is a coaxial type downhole heat exchanger named and proposed by the authors and others (Morita *et al.*, 1985; Morita and Matsubayashi, 1986). The major features of the DCHE include the utilization of a highly insulated inner pipe, reverse circulation (i.e., cold water down the annulus and hot water up through the inner pipe) and a completely closed system The authors have revealed by numerical simulations that highly efficient heat extraction can be performed with the DCHE (Morita *et al.*, 1985; Morita and Matsubayashi, 1986).

Fig. 2 (Morita and Matsubayashi, 1986) shows the effect of the thermal conductivity of the inner pipe on the temperature distribution in the coaxial type heat exchanger in the case of reverse circulation. Reverse circulation minimizes possible heat loss from the heat exchanger to the surrounding formation and maximizes the heat extraction interval. This results in a longer heat extraction interval.

It can be seen from this figure that the lower the thermal conductivity (i.e., the higher the insulation performance) of the inner pipe, the higher the hot water temperature at the outlet of the heat exchanger. The hot water temperature in the case of 0.01 W/m·K of thermal conductivity is



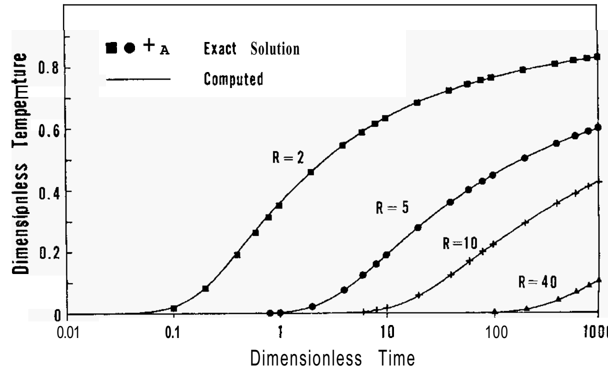


Fig. 3 Changes in medium temperatures at specified dimensionless radii (R) with dimensionless time.

heat is transferred in the vertical direction only in the flowing water in the wellbore, and

2) The thermal capacity of the inner pipe is negligible when there is forced flow in the wellbore.

In order to evaluate the accuracy of the simulator in conduction problem computations, comparisons with theoretical solutions and computations were made for two kinds of problems regarding an infinite length of circular cylinder surrounded by an infinite medium. One is the problem of the constant surface temperature of the cylinder, and the other is the problem of the constant current heating of the cylindrical heater.

Fig. 3 (Morita *et al.*, 1984) shows the results of a comparison between the exact solution given by Carslaw & Jaeger (1959; Equation (3), pp .342) and the values computed by the simulator in the case of a constant surface temperature of the cylinder. This figure shows temperature changes of the medium at specified dimensionless radii (R) with dimensionless time. The values for the exact solution are those computed by Jaeger (1956). As shown in the figure, both the exact solution and values computed by the simulator agreed with each other quite well. This indicates that the simulator gives very precise temperatures in the formation.

Fig. 4 (Morita and Kimura, 1992) shows the results of a comparison between the asymptotic solution given by Carslaw & Jaeger (1959: Equation (18), pp. 345) and the computed values in the case of a constant current heating of the perfect conductor cylindrical heater. The asymptotic solution is for large values of dimensionless time. This figure shows changes of deviation between the computed temperature of the heater and the asymptotic solution in the case of no contact resistance between the heater and the medium.

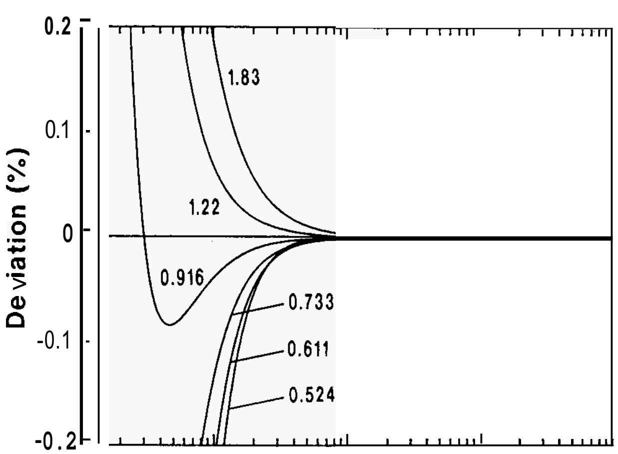


Fig. 4 Changes in deviation of heater temperatures between the asymptotic solution and computed values. The numbers in the figure denote thermal capacity ratios between the medium and the heat source.

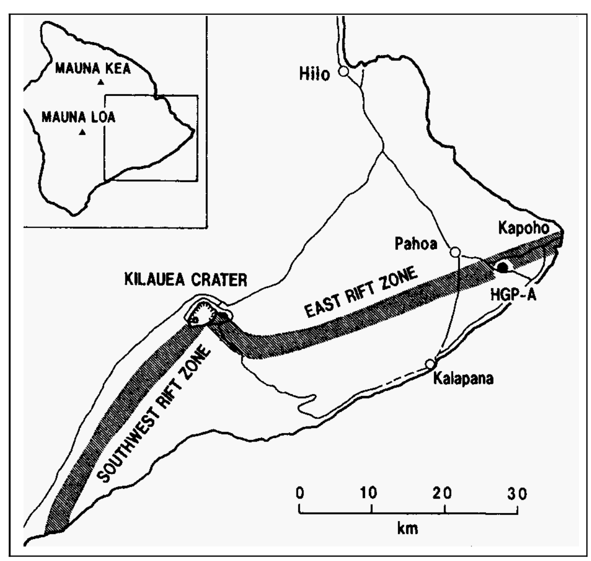


Fig. 5 The Island of Hawaii and the location of the HGP-A well.

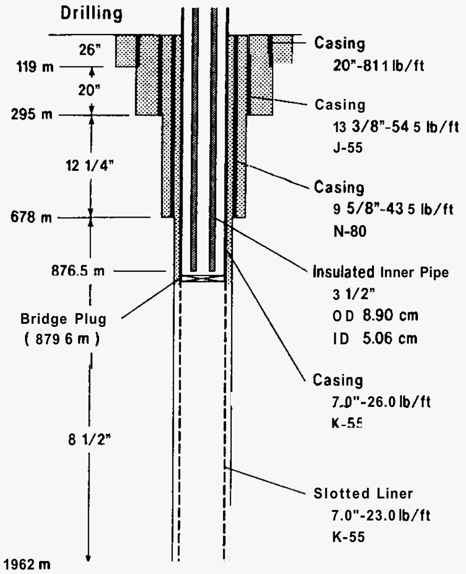


Fig. 6 The drilling and casing profile of the HGP-A well along with the DCHE formed in the well.

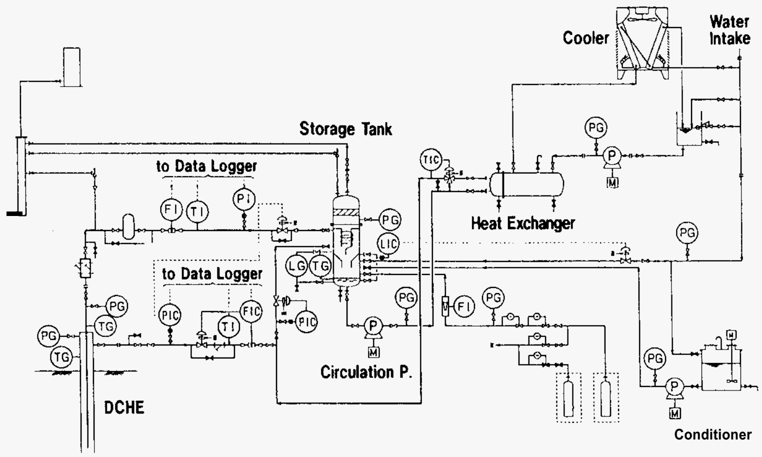


Fig. 7 Flow Diagram of the experimental system

Excellent agreement between the asymptotic solution and the computed values in large dimensionless time can be seen in the figure. This indicates that the simulator can calculate the energy balance between the outer surface of the heat exchanger and the surrounding formation with a high level of accuracy. The deviations in small dimensionless time are inferred to be mainly due to the errors associated with the asymptotic solution. It should be noted that the asymptotic solution is for large dimensionless time as described earlier.

The accuracy of the simulator was evaluated by comparing the data acquired by a field experinlent and the computed values with the simulator (Morita *et al.*, 1984). In order to acquire the necessary data, a circulation experiment in a well was carried out using the HY-2 well located at the former test site for the Hot Dry Rock project in the Yakedake area, Gifu prefecture, Japan. The results of the comparison between the measured and computed temperatures indicated that the simulator is sufficiently utilizable for coaxial type heat exchangers.

3. THE MEASUREMENT EXPERIMENT

The measurement experiment was carried out using the HGP-A well on the island of Hawaii as a cooperative project between the Pacific International Center for High Technology Research, USA and the Engineering Advancement Association of Japan (Morita *et al.*, 1992 a, b).

The HGP-A well is located in the lower Kilauea East Rift Zone (see Fig. 5). The well was used as the only production well for a 3 MW power generation pilot plant, and was shut down in December 1989 when plant operation was terminated. The well had been shut for ca. 12 months until January 1991 when preparatory work for this experiment began.

Fig. 6 shows the drilling and casing profile of the well along with the DCHE formed in the well. The depth of the well is 1,962 m. The experiment was carried out within a 7.0" casing interval from February 22 to March 1, 1991. The test duration was seven days. A total of 74 pieces of 3.5" vacuum type double tube insulated pipes were used as the inner pipe of the DCHE. The bottom-end of the insulated inner pipe was 876.5m in depth. A bridge plug was set at 880m in depth to prevent out-flow of working fluid from the test section.

The formation surrounding the HGP-A well consists only of basaltic rock along the entire length of the well. This means that the well is very suitable for evaluating the accuracy of the *in situ* thermal conductivity measurement method.

The formation from the ground surface to 450 m in depth consists of derivatives of surface eruptions such as a'a and pahoehoe lava, cinder and clinker. The interval from 450 m to 700 m is a transition zone consisting of derivatives from the surface eruptions and sea floor eruptions. Below 700 m, there is a sea floor eruption zone consisting of pillow lava. The ground water level at the site is ca. 175 m in depth.

Fig. 7 shows the flow diagram of the experimental system Tap water was used as the working fluid. With this system the flow rate, pressure and temperature of the injected water into the DCHE were automatically maintained at set values during the experiment. The set values of flow rate, temperature and pressure of injected water were 80 *l*/min., 30°C and 0.15 MPa at gage, respectively. The length of the injection and production lines between the main surface facility and the well head were 28 m, and they were thermally insulated.

Flow rate, temperature and pressure of water in both injection and production lines, hot water temperature at the bottom of the DCHE and ambient temperature were measured continuously during the experiment. Resistance temperature detectors were used for measurement of water temperatures in both surface lines. For logging data, a Campbell Scientific Inc. data logger (Model CR-21X) was used.

Fig. 8 shows the results of several temperature logs in the HGP-A well. The temperature histories before each log are different. From these measured temperature distributions, it is inferred that convection is the dominant heat transfer nlechanism in the intervals from the ground surface to ca. 300 m in depth and below ca. 1,200 m in depth. since the temperature gradients and the differences between each log are comparatively small in these intervals (hereinafter, these intervals are called the upper or lower convection dominant zone). Conversely, it can be inferred that conduction is dominant in the interval between ca. 300 m and 1,200 m in depth (hereinafter, this interval is called the conduction dominant zone).

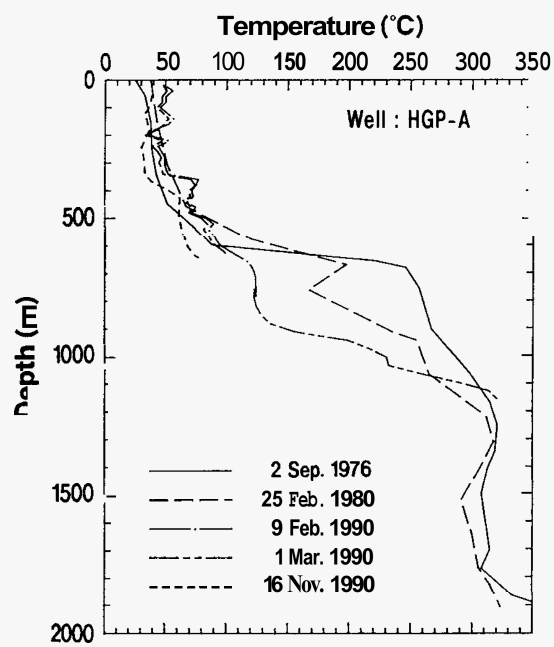


Fig. 8 Results of several temperature logs at the HGP-A Well.

For the measurement of *in situ* thermal conductivity, the conduction dominant zone was targeted to make possible the evaluation of the accuracy of the measured thermal conductivity. Hence, the injection temperature of the water was set to 30°C , which is almost the same temperature as that measured in the upper convection dominant zone, to eliminate the effect of the heat transfer characteristics of the upper convection zone on produced hot water temperature.

Both injected and produced cumulative mass flows were almost the **same** throughout the experiment. This indicates that there was no detectable out-flow or in-flow from the DCHE during the experiment. Hence, in the analysis, the mass flow rate was assumed to be unifonn throughout the DCNE and equal to the measured mass flow rate in the injection line.

4. DETERMINATION OF IN *SITU* THERMAL CONDUCTIVITY

As described before, the *in situ* thermial conductivity of the formation was determined by carrying out simulations. Table 1 shows the physical properties of materials used in the simulations. Properties of water-saturated basalt were assumed as formation properties, since the entire interval of the HGP-A well consists of basaltic rock.

Table 1 Physical properties **of** materials used in the analysis.

Materials	Specific Weight (kg/m³)	Specific Heat (J/kg·K)	Thermal Conductivity (W/m·K)	**Comments**
Steel	[illegible]		46.1	
Cement	1,830	1,900	0.99	**water saturated**
Formation	3,050	870	to be estimated	values for porosity = 0 %

The specific weight shown in the table is a true specific weight calculated from Robertson and Peck's data (1974) for Hawaiian basalt. The value of 3,050 kg/m^3 is an average of 30 samples whose porosities are less than or equal to 30%. The specific heat of 870 J/kg·K is a value for basalt at 70°C (Touloukian and Ho, 1981). 70°C is an average initial temperature at near ground surface and the bottom-end of the inner pipe. Both the specific weight and specific heat of the formation at specified porosities were calculated from these values and used in the analysis.

Fig. 9 shows the temperature distribution model at the HGP-A well within the test interval. The model was determined by referring to two measurements made 7 days and 1 day prior to the onset of the experiment and used for this analysis. The temperature at the bottom of the test interval in this model is 110.3°C.

First, the insulation performance of the inner pipe was determined. The insulation performance or equivalent thermal conductivity of the inner pipe can be determined as the thermal conductivity which gives the same temperature drop between the bottom-end and the outlet of the DCHE as the one measured (ca. 1.2°C at 93 hours in elapsed time, see Fig. 12).

Since the temperature drop is not very sensitive to the physical properties of the fommtion, the insulation performance can be determined using approximate physical properties of the formation. As a result, the insulation performance was determined to be 0.06 W/m·K.

Then, the thermal conductivity of the formation was investigated. The thermal conductivity of the formation can be determined as a thermal conductivity which gives a similar change in produced hot water temperature to the measured change as described earlier. Here, the equivalent thermal conductivity of the inner pipe was fixed at the estimated value, 0.06 W/m·K, in all the simulations.

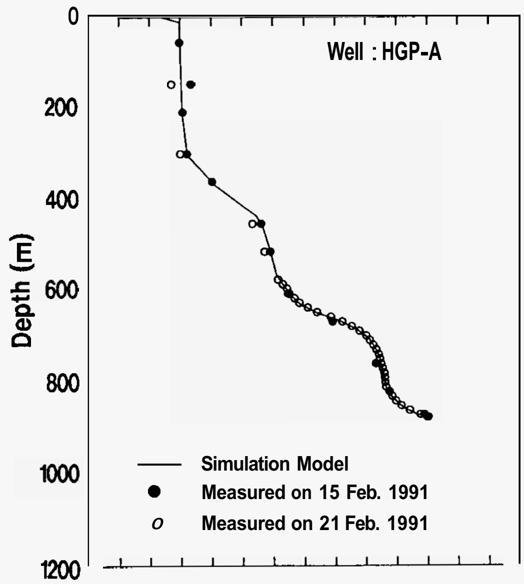


Fig. 9 Undisturbed formation temperature distribution model used in the analysis.

After several trial simulations, it was shown that the heat transfer mechanism in the formation during the experiment was almost pure conduction and that the thermal conductivity of the formation was ca. 1.6 W/m·K. This value is concordant with the thermal conductivities of the water-saturated Hawaiian basalt measured by Robertson and Peck (1974).

Therefore, the investigation was carried out assuming that the thermal conductivity of the formation followed the relationship between the porosity and the thermal conductivity of the water-saturated Hawaiian basalt correlated by Horai (1991) using Robertson and Peck's data (1974) hereinafter.

Fig. 10 shows the measured thermal conductivities of Hawaiian basalt by Robertson and Peck (1974) and the relationships between the porosity and thermal conductivity correlated by Horai (1991). The relationships shown by solid and dashed curves indicate the relationships correlated using Fricke-Zimmerman's formula and Maxwell's formula, respectively. Here, the relationship correlated using Fricke-Zimmerman's formula was used in the analysis.

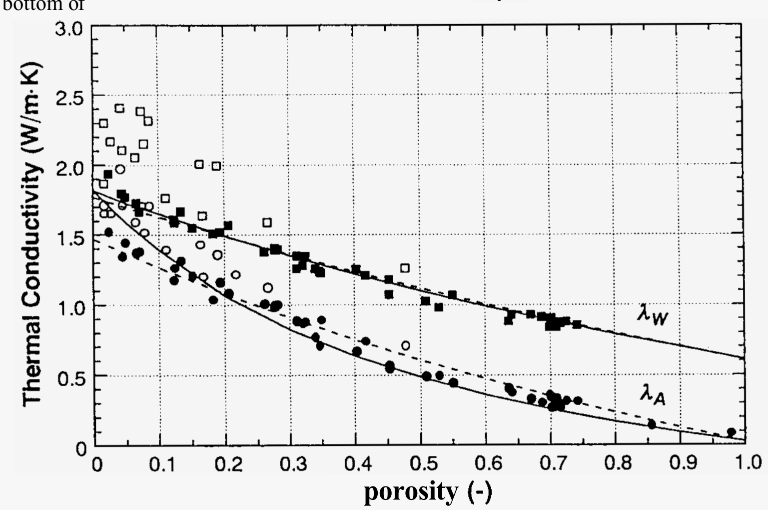


Fig. 10 The relationship between porosity and the thermal conductivity of Hawaiian basalt correlated by Horai (1991). Solid and open symbols denote that the values for the modal content of olivine are less than 5% and greater than 5%, respectively. "λ_A" and "λ_W" in the figure denote the thermal conductivities in air-saturated or water-saturated states, respectively.

Fig. 11 shows the procedure used to determine the thermal conductivity (λ) of the formation. The symbols C_p, γ, λ and ϕ in the figure denote specific heat at constant pressure, specific weight, thermal conductivity and porosity of the formation, respectively. Following the procedure, thermal conductivity of the formation was estimated to be 1.60 W/m·K. The estimated porosity, specific weight and specific heat of the formation corresponding to the estimated thermal conductivity are 13%, 2,784 kg/m^3 and 1,026 J/kg·K, respectively.

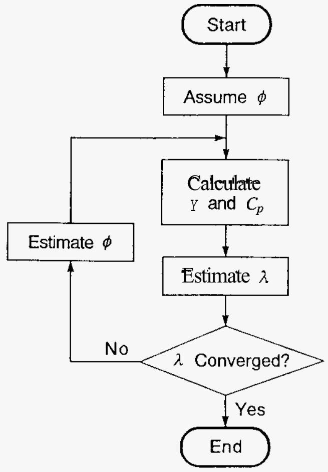


Fig. 11 The procedure to determine the thermal conductivity of the formation.

Fig. 12 shows the temperature distribution in the DCHE at 93 hours in elapsed time from the onset of the experiment.

The computed values shown in this and succeeding figures are the values computed using the estimated insulation performance of the inner pipe and the estimated physical properties of the formation.

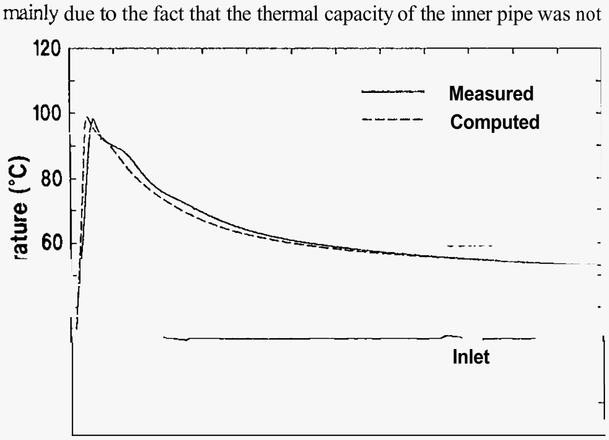
As shown in the figure, the difference between the temperature of water in the annulus and the initial formation temperature was almost the same in the upper convection dominant zone between the ground surface and ca. 300 m in depth.

This indicates that little energy was extracted from the upper convection dominant zone during the experiment and that the effect of the heat transfer characteristics of the upper convection dominant zone on the produced hot water temperature was very slight or negligible. Hence, the observed temperature of the produced hot water and the change in this temperature can be regarded as solely reflecting the heat transfer characteristics of the conduction dominant zone.

Figs. 13 (a) and (b) show changes in injected and produced water temperatures. Fig. 13 (a) is for up to 12 hours in elapsed time, while Fig. 13 (b) is for the entire test duration. The measured inlet temperatures shown in the figures were used in the simulations.

In Fig. 13 (a), a slight difference between measured and computed outlet temperatures is observed in the period from the onset of the experiment up to 8 hours in elapsed time. However, except for during this period, both measured and computed values agreed quite well.

The slight difference in the early stage of the experiment is inferred to be mainly due to the fact that the thermal capacity of the inner pipe was not



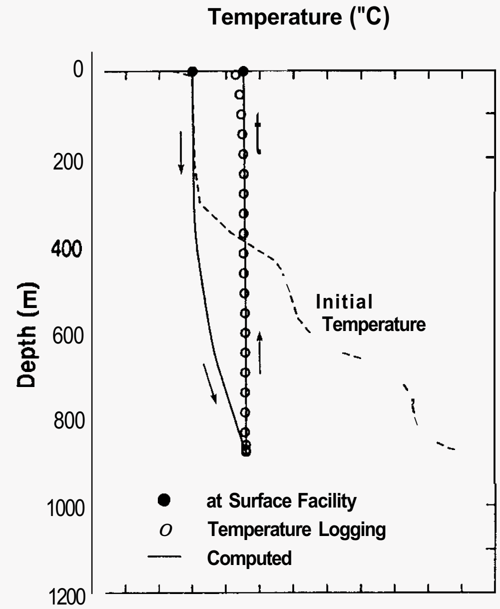


Fig. 12 Temperature distribution in the DCHE during circulation at 93 hours in elapsed time.

taken into account in the simulation, since the tendency of this difference can be explained well by this. Also, the good agreement between the amount of heat to be released from the inner pipe in the early stage of the experiment and the difference between measured and computed cumulative net thermal outputs corresponding to the same period reinforce this explanation (Morita *et al.*, 1992b).

In Fig. 13 (b), it is difficult to distinguish the difference between the measured and computed hot water temperature changes even in the period just after the power failure.

Because pure conduction was assumed in the simulation, such good agreement indicates that the heat transfer mechanism in the interval between ca. 300 m in depth and the bottom of the DCHE is almost pure conduction. This heat transfer mechanism is concordant with the mechanism inferred from the temperature distributions shown in Fig. 8. This indicate that the interval between ca. 300 m and 1,200 m in depth is a low permeability conduction zone, in other words, the cap rock of the HGP-A reservoir.

The sensitivity of produced hot water temperature to the thermal conductivity of the formation was 0.1°C per 0.01 W/m·K at the end of the experiment in the simulations. Thus, it was possible to determine the thermal conductivity up to the second decimal place (i.e., 0.01 W/m·K) in this analysis. However, taking into account possible errors associated with measurement and simulations, the thermal conductivity of 1.6 W/m·K is recommendable as the *in situ* thermal conductivity.

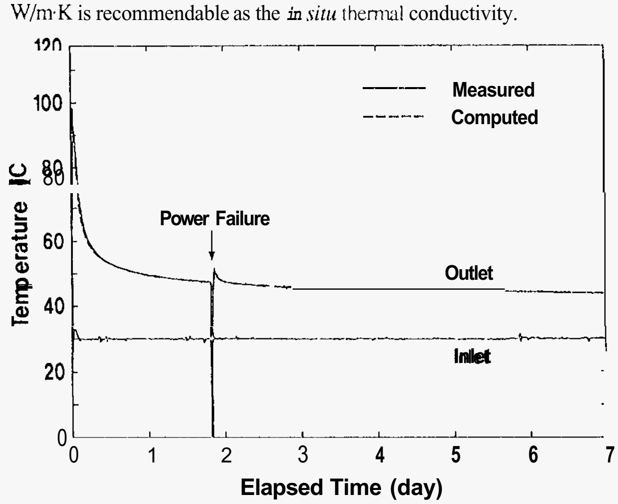


Fig. 13 (b) Changes in inlet and outlet water temperature for the entire duration.

5. EVALUATION OF THE ACCURACY OF ESTIMATED THERMAL CONDUCTIVITY

The heat transfer mechanism in the measurement interval was identified as almost pure conduction and the *in situ* thermal conductivity was estimated to be 1.6 W/m·K. The identified heat transfer mechanism is concordant with the mechanism inferred from the measured temperature distributions in the well. Thus, the accuracy of the estimated thermal conductivity may be the most interesting point of this analysis.

It is normally difficult or impossible to evaluate the accuracy of the estimated *in situ* thermal conductivity, since the formations are generally complex and sometimes there is convection in the formation.

However, the formation at the HGP-A well consists of only basaltic rock and the measurement was carried out in the interval where the heat transfer mechanism is almost pure conduction. In addition, regarding Hawaiian basalt, there is sufficient data on its thermal conductivity. These facts make it possible to evaluate the accuracy of the estinlated thermal conductivity.

Here, the authors try to evaluate the accuracy of estimated thermal conductivity using the relationship correlated using Fricke-Zimmernian's formula by Horai (1991).

The authors could not find any data regarding the *in situ* porosity of the formation at the well. However, in an almost pure conduction zone, the possible range of *in situ* porosity should be limited to a narrow range.

If the average porosity of the formation is assumed to be 20%, which is presumably much greater than that of the actual porosity, the thermal conductivity of the formation is estimated to be ca. 1.5 W/m·K from the relationship shown in Fig. 10. If the porosity is assumed to be 0%, the value is estimated to be ca. 1.8 W/m·K. Therefore, the possible error in the estimated thermal conductivity is inferred to be within - 0.1 to + 0.2 W/m·K. This range is similar to the errors associated with ordinary laboratory thermal conductivity measurements. Also, taking into account the high accuracy of the simulator in conduction problem computations, it is inferred that the actual error is much smaller than the minimum or maximum values of the range mentioned above.

Regarding the porosity of the formation, the estimated value (i.e., 13%) seems to be somewhat greater than expected for the conduction zone of the formation. This may be due to the relationship used for the determination of the thermal conductivity. The relationship is the one correlated using the values measured at room temperature. Since the authors have no information regarding the dependence of the thermal conductivity of Hawaiian basalt on temperature, the dependence was not taken into account in this analysis.

The thermal conductivity of basalt normally decreases with increasing temperature (e.g., Touloukian and Ho, 1981). Thus, there is a possibility of shifting the relationships shown in Fig. 10 several percent downward and to decrease corresponding porosity at the measurement temperature condition in this experiment. *Also,* the authors would Like to emphasize that the possible difference in porosity doesn't affect the estimated and rounded thermal conductivity of 1.6 W/m·K. In the simulations carried out in this study, the effect of differences in porosity itself on the estimated thermal conductivity was very slight.

6. CONCLUSIONS

The authors have measured *in situ* heat transfer characteristics with the DCHE at the HGP-A well on the island of Hawaii. The heat transfer mechanism in the measurement interval was identified as almost pure conduction. This heat transfer mechanism is concordant with the inferred mechanism from the measured temperature distributions in the well. This experiment might be the first time that the existence of a conduction zone or a cap rock above a geothermal reservoir was identified by the heat transfer mechanism of the formation. The *in situ* thermal conductivity of the conduction zone was estimated to be 1.6 W/m·K and the possible error associated with the value was inferred to be within - 0.1 to + 0.2 W/m·K. These results indicate that the DCHE can be used as an accurate *in situ* thermal conductivity measurement probe.

As described in this paper, it is possible to measure average *in situ* thermal conductivities for long intervals by this method even if the temperature of the formation varies with depth. In the experiment reported here, flow rate, temperature and pressure of injected water were kept constant. However, this is not necessary for measurement of *in situ* thermal conductivity when a numerical simulator is used for the analysis. Therefore, this measurement system can be more simplified than that used at the HGP-A well. Thus, the method reported in this paper is thought to be practical and convenient for the measurement of *in situ* thermal conductivity.

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