

ANALYSIS OF THE RESULTS
FROM THE DOWNHOLE COAXIAL HEAT EXCHANGER (DCHE)
EXPERIMENT IN HAWAII

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ABSTRACT

Analysis of the experimental results from the DCHE experiment (Morita *et al.*, 1992) was carried out to investigate the insulation performance of the inner pipe used in the DCHE and the heat transfer characteristics in the formation. The equivalent thermal conductivity of the pipe was estimated to be 0.06 W/m·K. This indicates that the performance of the insulated pipes used as the inner pipe is sufficiently high for DCHE application. Analysis also indicated that the heat transfer mechanism during the experiment was almost pure conduction and that the thermal conductivity of the formation was 1.6 W/m·K. This value is concordant with the thermal conductivity of water-saturated Hawaiian Basalt (Horai, 1991). Also the fact that the observed heat transfer mechanism in the formation was pure conduction indicates that heat was extracted mainly from a low permeability conduction zone of the HGP-A reservoir.

INTRODUCTION

From February 22 to March 1 in 1991, the first DCHE field experiment was carried out successfully on the Island of Hawaii as a joint project between the Pacific International Center for High Technology Research (PICHTR) and the Engineering Advancement Association (ENAA) of Japan. The main purpose of this experiment was to prove the concept of DCHE using the HGP-A well located in the Kapoho area in Puna. An interval from the surface down to 876.5m in depth was used for the experiment. Flow rate, temperature and pressure of the injected water were fixed at 80 l/min, 30°C and 1.5 kgf/cm² (gage), respectively, throughout the experiment. The details of the experiment are described in separate paper (Morita *et al.*, 1992).

METHOD OF ANALYSIS

This analysis was carried out by performing numerical simulations. The simulator developed by Morita and others (Morita *et al.*, 1984; Morita and Matsubayashi, 1986) was used for the analysis. The simulator employs an explicit form finite difference method to solve heat conduction problems in the formation.

Major Assumptions Employed for the Analysis

The following assumptions were employed in the analysis:

- (1) In the formation, heat is transferred to the wellbore only in the radial direction by conduction. Throughout the entire system, only flowing water in the DCHE transfers heat in the vertical direction, and
- (2) Thermal capacity of the inner pipe is negligibly small when there is flow in the DCHE.

Given these assumptions, it was hypothesized that the existence of convection in the formation would be detectable as differences between the computed and measured hot water temperature changes.

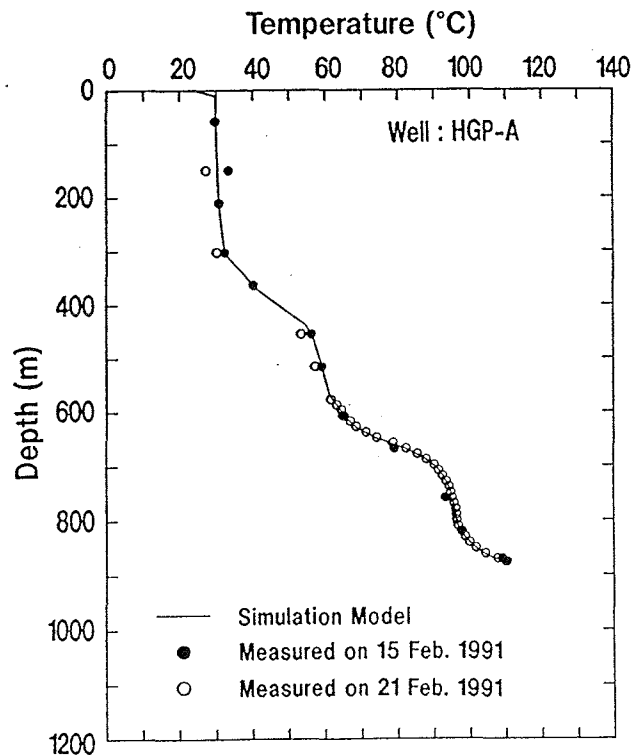


Fig.1 Temperature distribution model used in the analysis.

Table 1. Physical properties of materials.

Materials	Specific Weight (kg/m ³)	Specific Heat (J/kg·K)	Thermal Conductivity (W/m·K)	Comments
Formation	3,050	870	to be estimated	values for porosity =0%
Cement	1,830	1,900	0.99	water saturated
Steel	7,850	470	46.1	

Model and Conditions Used in the Analysis

The temperature distribution used for the analysis is shown in Fig.1. This model was determined by referring to two measurements made with the Kuster tool carried out 7 days and then 1 day before the onset of the experiment. The elapsed time from the shut-in of the well to the measurements was about fourteen months.

The casings, cement and insulated inner pipe shown in separate paper (Morita et al.,1992) were modeled as closely as possible. However, the portion below the bottom-end of the insulated pipe was not modelled because of the radial heat transfer assumption stated previously.

Physical properties of the materials used in this analysis are shown in Table 1. Properties of water-saturated basalt were assumed as formation properties since entire interval of the HGP-A well consists of basaltic rock. The specific weight shown in the table is a true specific weight calculated from Robertson and Peck's data (1974) for Hawaiian basalts. The value is an average value for 30 samples whose porosities are less than or equal to 30%. The specific heat is a

value of 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 specific weight and specific heat of the formation at specified porosities were calculated from these values and used in this analysis.

Since the injected and produced cumulative mass flows during the experiment were almost the same (Morita et al.,1992), the mass flow rate was assumed to be uniform throughout the DCHE and equal to the measured mass flow rate in the injection line.

The length of the injection or production lines were 28m each. However, both lines were thermally insulated. Therefore, the temperatures of injected or produced water measured at the main surface facility were considered to be the temperatures at the inlet or outlet of the DCHE in this analysis.

Pressures of injected or produced water measured at the facility were converted into the pressures at the inlet or outlet of the DCHE using measured pressure drops shown in Fig. 2 and they were used in this analysis.

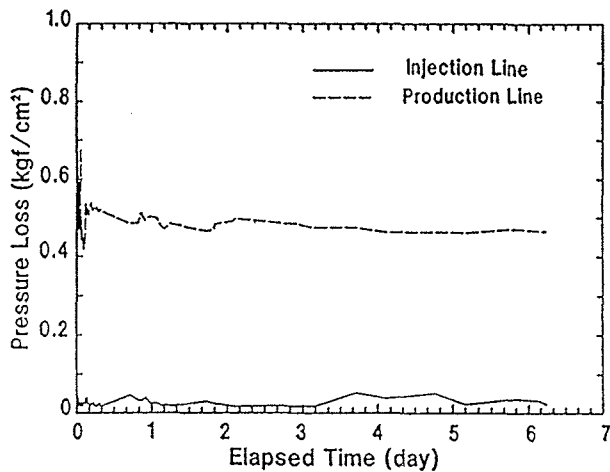


Fig.2 Measured pressure drops in the surface injection and production lines.

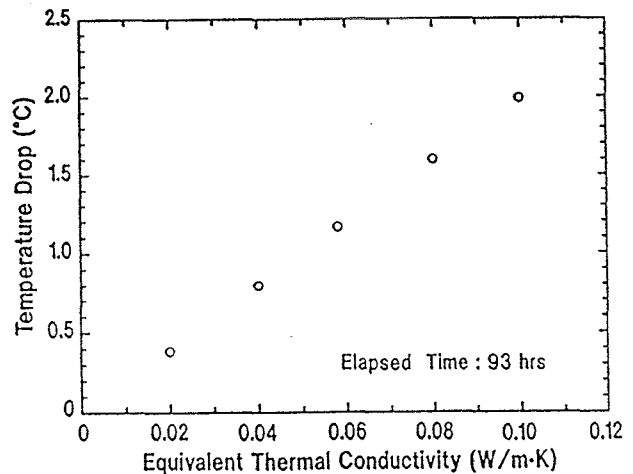


Fig.3 Relationship between the equivalent thermal conductivity of the pipe and the temperature drop.

RESULTS OF THE ANALYSIS

Estimation of the Insulation Performance of the Inner Pipe

One of the objectives of the field experiment was to obtain a value of the equivalent thermal conductivity for the insulated inner pipe *in situ*.

Since the temperature drop in the pipe is not very much sensitive to the physical properties of the formation, the equivalent thermal conductivity can be estimated by using the temperature drop between the bottom-end (downhole) and the outlet of the DCHE, and assumed properties for the formation. In this case, the temperature drop was estimated to be 1.2°C from the data collected during a temperature log performed on February 26 (Morita et al., 1992). The physical properties of the formation consistent with the values from Horai (1991) were assumed.

The equivalent thermal conductivity was investigated by performing iterative simulations in which the thermal conductivity was varied. The resulting value of the thermal conductivity of the pipe was the value which gave the same temperature drop at the logging time.

Fig.3 shows the relationship between the equivalent thermal conductivity of the pipe and the computed temperature drop at the middle of the logging period, i.e., 93 hours from the onset of the experiment. From the figure, it can be observed the same temperature drop occurs when the pipe's thermal conductivity is 0.06 W/m·K. Therefore, the equivalent thermal conductivity of the pipe is estimated to be 0.06 W/m·K.

Heat Transfer Mechanism and Thermal Conductivity of the Formation

The effective thermal conductivity of the formation can be investigated as a thermal conductivity which gives the same change in produced hot water temperature as the measured change. Here, the equivalent thermal conductivity of the inner pipe was fixed at the estimated value, 0.06 W/m·K, in all the simulations. 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 about 1.6 W/m·K. The value is concordant with the thermal conductivity of water-saturated Hawaiian basalt (Horai, 1991). Therefore, the investigation was carried out assuming that the thermal conductivity of the formation followed the relationship between the porosity and thermal conductivity of the water-saturated Hawaiian basalt obtained using Fricke-Zimmerman's formula by Horai (1991) afterward.

Fig.4 shows the procedure used to investigate the thermal conductivity (λ) of the formation. Following the procedure, thermal conductivity of the formation was estimated to be 1.60 W/m·K. According to Horai(1991), the porosity (ϕ) of the water-saturated basalt which gives the same thermal conductivity is about 13%. Apparent

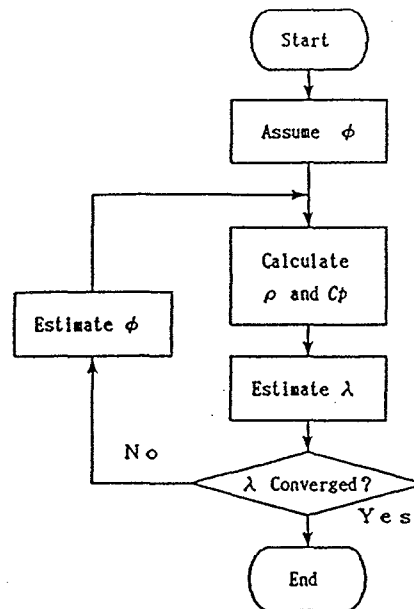


Fig.4 The procedure to investigate the thermal conductivity of the formation.

specific weight (ρ) and specific heat (C_p) of the water-saturated basalt at the same porosity were calculated to be 2,784 kg/m³ and 1,026 J/kg·K, and these were the values used in the simulation to confirm the thermal conductivity to be 1.60 W/m·K.

COMPARISON BETWEEN MEASUREMENT AND COMPUTATION

The comparison between measured and computed values such as hot water temperature or pressure is shown in the following figures. Computed values in all the figures are the values computed using estimated conductivities, 0.06 W/m·K as the equivalent thermal conductivity of the inner pipe and 1.60 W/m·K as the thermal conductivity of the formation.

Change in the Hot Water Temperature

Figs. 5(a) and (b) show changes in water temperatures at the surface in the early stage of the experiment and over the entire experimental period, respectively. The measured inlet temperatures shown in the figures were used in the simulations as the inlet temperature of the DCHE. In Fig.5(a), a slight difference between measured and computed values is observed in the period from the onset of the experiment up to 8 hours in elapsed time. However, after that period, it becomes difficult to distinguish the differences between the measured and computed temperatures even in the period just after the power failure. As described previously, pure conduction was assumed to be the heat transfer mechanism in the formation in this analysis. Hence, the excellent agreement between measured and computed temperatures as shown in Fig.5(b) indicates that the heat transfer mechanism in the formation during the experiment was almost pure conduction.

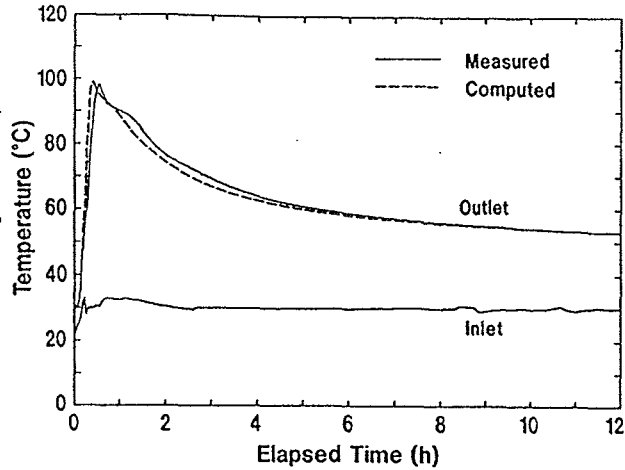


Fig. 5(a) Changes in inlet and outlet water temperature of the DCHE up to 12 hours.

The slight difference in the early stage of the experiment is probably due to the fact that the thermal capacity of the inner pipe was not taken into account in the simulation. In reality, the pipe has thermal capacity. Hence, during the period of increase in hot water temperature, a certain amount of heat from up-flowing hot water is absorbed into the inner pipe. This results in hot water temperature lower than the computed temperature and a delay in the time to reach the peak temperature. In contrast to this, in the period after the hot water temperature peak, heat is released from the pipe into the up-flowing hot water which results in hot water temperature higher than computed temperature. Thus, the differences in Fig. 5(a) are explained.

In addition to this, a certain amount of heat is released from the pipe with the process of the heat extraction, because the heat contained in the pipe decreases with the decreasing water temperature in the DCHE. Therefore a slightly greater measured cumulative net thermal output than that of the computed values should be observed.

The amount of heat contained in the pipe just before the onset, and 12 and 24 hours after the

Table 2. The amount of heat contained in inner pipe and to be released from the pipe.

Elapsed time	Heat Contained (kWh)	Heat to be released (kWh)
before onset	137	0
12 hours	104	33
24 hours	99	38

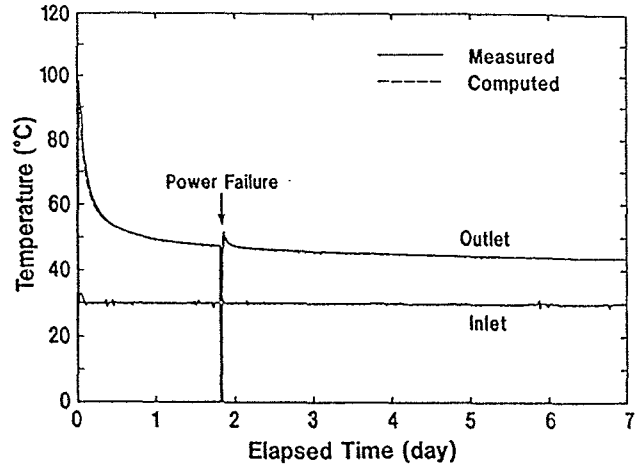


Fig. 5(b) Changes in inlet and outlet water temperature for entire test duration.

onset were calculated as shown in Table 2 assuming that temperatures of the outer and inner tubes of the pipe are the same as those of the water in the annulus or in the pipe. The initial temperature distribution in the formation and the computed temperature distribution in the DCHE for 12 and 24 hours were used in this calculation. Also the amounts of heat to be released from the pipe up to 12 and 24 hours were calculated to be 33 kWh and 38 kWh, respectively, as shown in Table 2. The differences between measured and computed cumulative net thermal output at the same time point are 37 kWh and 41 kWh, respectively, as shown in Fig. 6. These values are almost the same as the amount of heat to be released from the pipe.

Therefore, it is thought that the major portion of the difference in the early stage of the experiment was due to the assumption employed in the simulation.

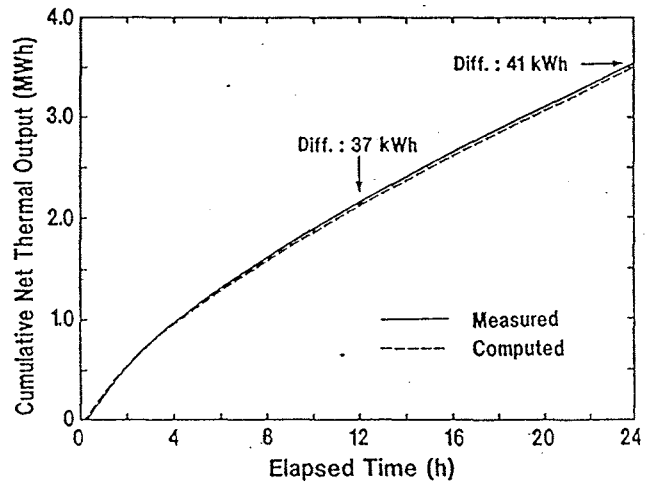


Fig. 6 The difference between measured and computed cumulative net thermal outputs up to 24 hours in elapsed time.

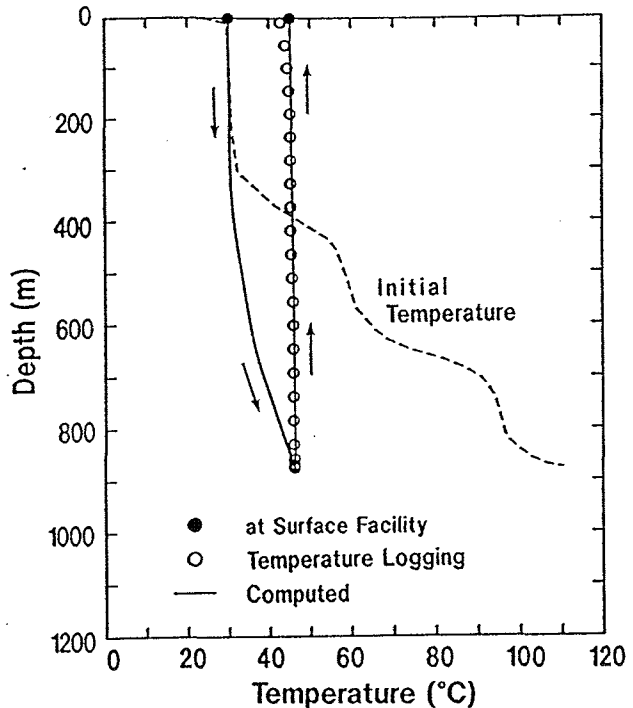


Fig. 7 Temperature distribution in the DCHE at 93 hours in elapsed time.

Temperature Distribution in the DCHE

Fig. 7 shows the temperature distribution in the DCHE at 93 hours from the onset. As shown in the figure, measured and computed temperatures agree with each other well. A slight difference can be observed in the temperatures measured using the Kuster tool and the one computed in the shallow interval (less than 200m depth). However, a major portion of this difference is probably caused by insufficient time to equilibrate the temperature of the tool to the measurement environment.

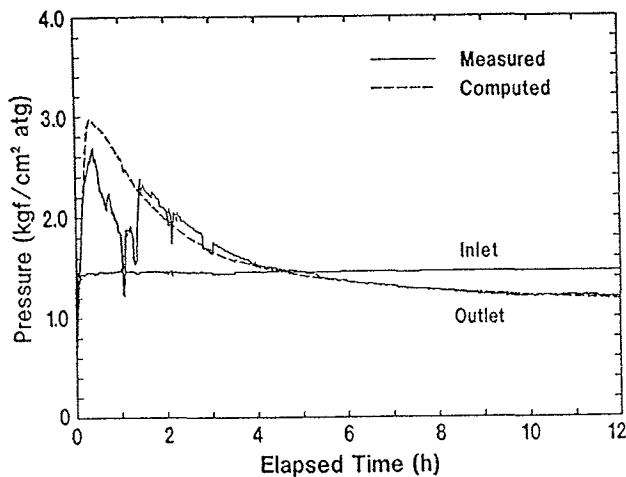


Fig. 9(a) Changes in the inlet and outlet water pressure up to 12 hours.

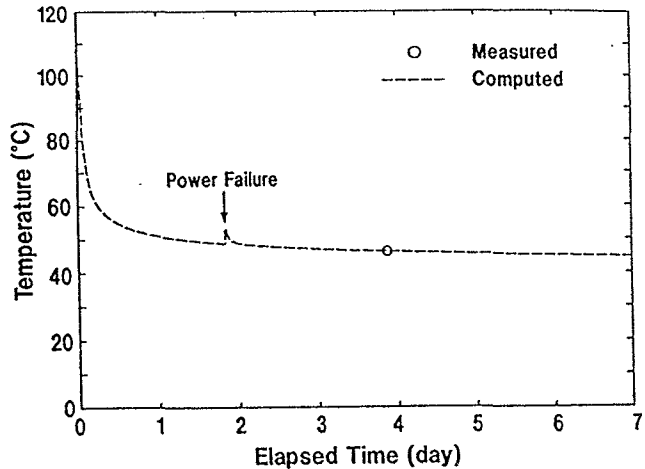


Fig. 8 The water temperature change at the bottom-end of the DCHE.

The figure also shows that the difference between the water temperature in the annulus and the initial formation temperature was very small in the interval between the surface and 300m in depth during the experiment. This indicates that only a small amount of heat was extracted from this interval during the experiment.

Temperature Change at the Bottom-end of the Inner Pipe

Fig. 8 shows the hot water temperature changes at the bottom-end of the inner pipe. Two techniques were used to measure the downhole temperature during circulation: one using a sheathed thermocouple attached to the insulated inner pipe and one using the Kuster tool. However, the data acquired by the sheathed thermocouple seem to be suspect, since there was a short circuit in the thermocouple, and were not used in the analysis.

Very good agreement between the measured and computed temperatures was obtained as shown in

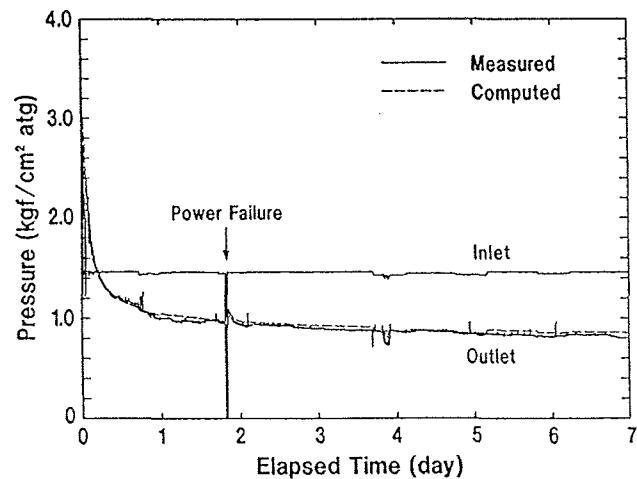


Fig. 9(b) Changes in the inlet and outlet water pressure for entire test duration.

Fig.8. In the case of the DCHE, the temperature change patterns for the hot water at the bottom-end of the pipe and the outlet of the DCHE are almost the same because a highly insulated inner pipe was utilized. Therefore, good agreement in hot water temperature change at the outlet of the DCHE reinforces the good agreement at bottom-end temperature.

Change of the Hot Water Pressure

Figs. 9(a) and (b) show changes in water pressures at the inlet and outlet of the DCHE in the early stage of the experiment and over the entire experimental period, respectively. The measured inlet pressures shown in the figures were used as the inlet pressure of the DCHE in the simulations.

Significant and irregular change in hot water pressure can be observed in Fig.9(a) during a period from the onset of the experiment up to 1 hour 22 minutes in elapsed time. The difference between the measured and the computed outlet pressure is rather great during this period. As described in a separate paper (Morita et al., 1992), a significant amount of cement and silica scale particles flowed out of the well during the initial portion of the test. Therefore, a major portion of the difference in hot water pressure during this period was probably caused by increased density of the hot water and/or changes in the concentration of particles in the up-flowing water.

After this period, slight difference could be still observed up to 6 hours or so in elapsed time. The major portion of this difference is probably due to the higher measured hot water temperature as shown in Fig.5(a), and the assumption as described previously. In general, the simulations carried out in this study resulted in good agreement in hot water pressures when the measured and the computed temperatures were in good agreement. One exception was the period up to 1 hour 22 minutes in elapsed time.

Except for the initial period described above, the difference between the measured and the computed outlet pressure was less than 0.1kgf/cm² throughout the experiment. This indicates that the simulator used in the analysis provides appropriate water pressure estimates.

DISCUSSION

Insulation Performance of the Inner Pipe

The insulation performance of the inner pipe was estimated to be 0.06 W/m.K in equivalent thermal conductivity, and the temperature drop coinciding with the performance was only 1.2°C. There still may be possibility of improving the insulation performance. However, with such a high insulation performance, the effect of the difference in the insulation performance on the heat extraction efficiency of the DCHE is slight (Morita and Matsubayashi,1986). Therefore, it can

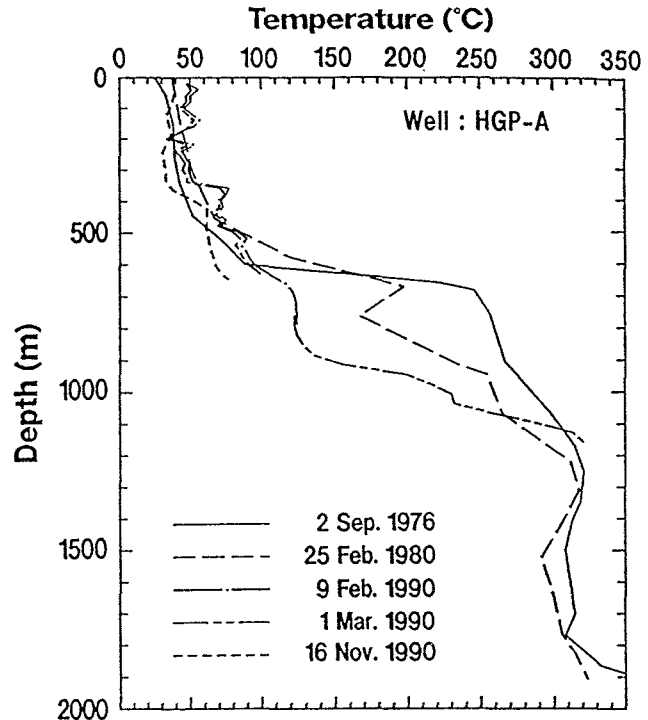


Fig. 10 Results of several temperature logs at HGP-A well.

be said that the insulation performance of the pipes used as the inner pipe in this experiment have already reached a sufficient level for DCHE application

Heat Transfer Mechanism in the Formation

From this analysis, it was indicated that the heat transfer mechanism in the formation during the experiment was almost pure conduction and that the thermal conductivity of the formation is 1.6 W/m.K. This suggests that there was no convection in the main heat extraction interval which affected the hot water temperature of the DCHE to a detectable degree.

Fig.10 shows the results of several temperature logs in HGP-A well. The temperature logs show that temperature gradients and the differences between each log are relatively small in the intervals from the ground surface to 350m in depth and deeper than 1,200m. They indicate that convection is a dominant heat transfer mechanism in these intervals. However, in the experiment, the difference between the temperature of water in the annulus and the initial formation temperature was very slight in the upper convective zone as shown in Fig.7. Therefore, very little heat was transferred in this interval to the working fluid. It should be noted that the lower convective zone was out of the test interval.

In contrast to these intervals, temperature gradients and the differences between each log are relatively great in the intervals from 350m to

1,200m. This indicates the possibility that conduction is the dominant heat transfer mechanism in this interval.

The effect of this interval on changes in the hot water temperature should have been much greater than in the shallow convective zone since the difference between the temperature of the water in the annulus and the initial formation temperature was much greater than that in the upper convective zone as shown in Fig.7.

The observed heat transfer mechanism in the formation during the experiment was almost pure conduction. Therefore, it is inferred that the heat transfer mechanism in this interval is also almost pure conduction. Furthermore, this indicates that the heat in this experiment was extracted mainly from a low permeability conduction zone of the HGP-A reservoir.

Thermal Conductivity of the Formation

The accuracy of the estimated thermal conductivity of the formation can be roughly evaluated assuming that the relationship between the solidity and the thermal conductivity of water saturated Hawaiian Basalt (Horai, 1991) can be applied to the formation surrounding HGP-A well.

If the average porosity of the formation is assumed to be 20% (which is presumably greater than that of the actual porosity), the thermal conductivity of the formation is estimated to be 1.5 W/m·K from Horai's figure. And if the value is assumed to be 0% (which is the minimum possible porosity), the conductivity is estimated to be 1.8 W/m·K. Therefore, the possible error in the estimated thermal conductivity is inferred to be within -0.1 W/m·K to + 0.2 W/m·K. This range is similar to that obtained in ordinary laboratory thermal conductivity measurements. Therefore, it is implied that the accuracy of the estimated thermal conductivity and the precision of the temperature calculation of the simulator used in this and previous DCHE analyses are very high.

CONCLUSIONS

The analysis of the data from the first field experiment of DCHE, which was conducted at the HGP-A well in Hawaii, was performed using the simulator developed by Morita and others (Morita

et al., 1984, Morita and Matsubayashi, 1986). The analysis resulted in very good agreement between theoretical predictions and measured values. Specifically, the analysis indicated that:

- (1) the equivalent thermal conductivity of the inner pipe under the test conditions was estimated to be 0.06 W/m·K;
- (2) the heat transfer mechanism in the formation at the main heat extraction interval was inferred to be almost pure conduction; and
- (3) the thermal conductivity of the formation was estimated to be 1.6 W/m·K which presumably represents the thermal conductivity of a low permeability conduction zone of the HGP-A reservoir.

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