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EVALUATION OF THE CURVE-FITTING METHOD AND THE HORNER-PLOT METHOD FOR ESTIMATION OF THE TRUE FORMATION TEMPERATURE USING TEMPERATURE RECOVERY LOGGING DATA

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ABSTRACT

This paper describes the method to estimate the true formation temperature using temperature recovery logging data after the well reach to total depth (T.D.). The method designated as "Curve-fitting method (CFM)" is based on mathematical model proposed by Middleton (1979, 1982). The accuracy and applicability of this method are evaluated with several field data and compared advantageously with the Horner-plot method.

Then, real-time data acquisition system including interpretation software has also been successfully developed.

As a conclusion, the followings are confirmed:

1) The developed CFM can be applicable to the estimation of the true formation temperature even using 24 hours temperature recovery data, although the Horner-plot method might need up to 120 hours recovery data, usually.

2) Though depending upon the quality of the data and/or number of the temperature recovery logging data, it might be possible to estimate the true formation temperature using less than 24 hours recovery data. Because, the computer program of this system has the function to decide when the measurement of temperature recovery logging should be finished.

1. INTRODUCTION

The true formation temperature is one of the important parameter for geothermal reservoir evaluation and it will be used if drilling of the well will be made complete or not when the well is reached to planned T.D. In order to obtain the true formation temperature, temperature recovery logs are most often carried out. Also, another important information of the fluid entry depth in the well will be obtained by these logs. If we could estimate the formation temperature using short period of logging data, it is very preferable to save the rig time and logging cost.

The Horner-plot method has been popularly used for estimating the formation temperature (Dowdle and Cobb, 1975). This method is easy to utilize even in the field, however on the other hand, it requires relatively long period of temperature recover data up to 120 hours to estimate correctly. It is also pointed out that the fluid circulation time as the Horner-time is very critical to the estimated result, therefore the Horner-time must be decided carefully.

Mathematical models for borehole temperature stabilization were proposed to estimate the true formation temperature. In this paper, these models were evaluated for the applicability to the estimation of the true formation temperature and the recovery temperature.

2. ESTIMATION OF THE TRUE FORMATION TEMPERATURE

2.1 Horner-Plot Method

The Horner-plot method as a formation temperature estimation which is based on an empirical analysis method that the phenomenon of temperature recovery after circulation has ceased in heat conductive geothermal well, is similar to the pressure build-up behavior of geothermal reservoir. The Horner-plot method proposed by Dowdle and Cobb (1975) gives a reliable static formation temperature in region of low geothermal gradient, and can be expressed the following formula:

$$BHTh = Tf + C \log\{(t+dt)/dt\} \quad (1)$$

Tf is the true formation temperature; t is the circulation time; dt is the elapsed time after circulation has ceased.

According to Dowdle and Cobb, comparative and analytical studies of the temperature build–up and pressure build–up using the diffusibility equation showed that the two methods are not completely analogous and Equ. (1) is not correct theoretically. Therefore, the method required long period of temperature recover time.

2.2 Curve–Fitting Method

(1) Curve–fitting method

The analytical CFM based on mathematical temperature stabilization has been proposed to calculate the true formation temperature with better accuracy even from shorter period of temperature recovery data by Luikov (1968), Carslaw and Jaeger (1959), and Middleton (1979, 1982). CFM calculates a static tempera–ture of the equilibrium formation by mathemati–cally represented the physical well model for temperature recover. Proposed mathematical model by Middleton was the temperature distri–bution in the center of the well with a vertical cylinder of infinite length, after circulation of drilling mud has ceased; BHTc(t) can be ex–pressed the following formula:

$$BHTc(t) = Tini + (Tf - Tini) \times \left\{ erfc\left(\frac{R}{(4Kt)^{1/2}}\right) \right\}^2 \quad (2)$$

t is the elapsed time after circulation has ceased; Tini is the initial temperature in the borehole at t = 0; Tf is the true formation temperature; R is the effective radius of the region affected by drilling; K is the thermal diffusibility of the well contents.

Fluid circulation time in drilling, which is re–quired for the Horner–plot method and also is a little uncertainty about adequate number, is not necessary in this model.

(2) Mathematical well models

Proposed several physical well models to ana–lyze the behavior of wellbore temperature recovery after circulation has ceased are exam–ined. The "Circular model" proposed by Luikov is assuming the physical well model as a circular cylinder (Fig. 1 (a)). The "Square model" proposed by Carslaw and Jaeger is assuming that a well can be approximated by a square cylinder as a physical well model (Fig. 1 (b)). Middleton proposed that a conductive heat transfer into a vertical, approximately cylindri–cal region of small diameter in rectangular coordinates leads to an expression for tempera–ture which is very much simpler than the corre–sponding expression in cylindrical coordinates (Fig. 1 (c)). Through case studies of these models using non–linear least squares fitting, results of calculated formation temperature from the model proposed by Middleton are evaluated more reliable and more accurate in comparison with field data. The reason why the most unreal Middleton's well model in three models calcu–lates most reliable and accurate results is ex–pected that the Middleton's model may be expressed realistic wellbore such as very rough shape and not gauged (Fig. 2).

(3) Inversion for CFM

Forward and inverse techniques as fitting method are examined. In forward technique, the formation temperature can be obtained by super–imposing a set of master curve, based on Equ. (2), on observed temperature data plotted at the same scale (similar to type–curve match–ing). However, many master curves are neces–sary to obtain accurate result, and it is very complicated work of trial and error, and also it's takes time.

Then, inverse technique which is non–liner least squares fitting method expressed in Equ. (3) is applied to obtain the formation temperature.

$$S = \sum_{i=1}^{n} \{BHTo(ti) - BHTc(Ti)\}^2 = Minimum \quad (3)$$

BHTo(ti) is the observed temperature at a time; BHTc(ti) is the calculated temperature at a time from Equ. (3); n is number of measured data. Where the effective radius; R and thermal diffu–sibility; K are expressed simply assumption following value α;

$$\alpha = \frac{R}{\sqrt{K}} \tag{4}$$

$$K = \frac{\lambda}{\rho c} \tag{5}$$

λ is the thermal conductivity; ρ is the density; c is the specific heat capacity. Therefore, in inverse technique, estimated true formation temperature can be obtained by iterate to minimize the sum of squares between BHTo and BHTc at a time. Features of a non-liner least squares method, in comparison with type-curve matching, are in its rapidity and objectivity. Therefore, we call this inverse method as CFM. Figure 3 illustrates an example of the non-liner least squares fitting result by inversion.

3. EVALUATION OF METHODS FOR ESTIMATING THE TRUE FORMATION TEMPERATURE

3.1 Estimated Formation Temperature by the Horner-Plot Method

Estimation of the true formation temperature by the Horner-plot method using experimental temperature recovery logging data which was performed at the LC-1 well in Kyushu, Japan is shown in Fig. 4. This graph shows that the Horner-plot method needs the temperature recovery logging data at least up to 48 hours, usually 120 hours of elapsed time to obtain the liner region in the Horner-plot. It is also confirmed that the value of circulation time is very essential to estimate correctly, otherwise it is very easily to miss-estimate 20-50°C.

3.2 Estimated Formation Temperature by Curve-Fitting Method (CFM)

Evaluation of CFM was performed using experimental temperature recovery data (Takai et al., 1994). Reliability and accuracy were exhaustively evaluated using elapsed time of temperature recovery log versus number of data and time interval as explained in Table 1. Through these case studies, it is verified that CFM can be suitable to estimate the formation temperature. That is, the accuracy of the estimated formation temperature using until 24.5 hours data is at most 5°C, and even using until 12.5 hours data, is at most 10°C. The computation time for CFM is less than 10 seconds using recent lap-top PC.

3.3 Comparison of Estimated Temperature

Figure 5 shows the cross plot of estimated formation temperature by the Horner-plot method (Tfbuild) and by CFM (Tffit) using 31 temperature recovery logs at 13 experimental wells in eight geothermal areas. Figure 5 (a) illustrates the cross-plot with the temperature recovery data up to 120 hours of elapsed time after the circulation ceased. The average error between both methods (Tffit - Tfbuild) is about -8.6°C (standard variation; $\sigma = 7.0$). Figure 5 (b) illustrates the cross-plot with the temperature recovery until eight hours. The average error of Tffit - Tfbuild is approximately -13.7°C ($\sigma = 9.4$). As shown in Fig. 5, the error becomes bigger in region where geothermal gradient is higher.

4. QUALIFICATION OF THE METHODS

Through the case studies, qualification of the methods can be concluded as follows.

4.1 Horner-Plot Method

One of the reason of difference between estimated temperatures by both methods shown in Fig. 5 can be understood that a main cause for the error in estimated temperatures by the Horner-plot method is insufficient temperature recovery log data and inexact circulation time. Therefore, it is possible to derive that bigger errors in estimated temperature by the Horner-plot method are the defect of this method for estimation of the true formation temperature in geothermal area where geothermal gradients are relatively high.

4.2 Curve-Fitting Method (CFM)

The mathematical model for CFM is based on the heat conductive formation model, therefore CFM cannot be applied to estimate formation temperature in non-conductive temperature distribution zone. From the same reason, CFM also cannot estimate the true formation temperature at lost circulation zone. If it is important to estimate the temperature in this zone, we need more study.

However, estimated temperature is not sensitive to the circulation time, therefore it is easier to use in the field and more accurate than the Horner-plot method.

5. SYSTEM DEVELOPMENT FOR FIELD APPLICATION

In order to apply CFM as a method for the true formation temperature estimation and/or recover temperature estimation at any elapsed time during temperature recovery logging in the field, real-time data acquisition system has been developed. Acquired data on field computer are processed almost real-timely, accordingly the estimated temperature can be calculated at every depth just after the temperature recovery log has been run.

This computer program has the function for evaluation of the reliability of the estimated temperature. Then, the engineer can use this information for his decision making when temperature recovery logs shall be finished. This function will help to keep the accuracy of the measurement, and to save the rig time and logging cost. As a function to decide termination of temperature recovery log, the following parameters are calculated and plotted;

1) standard deviation,
2) transition of difference of the estimated temperature (Tffit(n) – Tffit(n–1)),
3) standardized sum of squares by number of data, and
4) transition of the estimated true formation temperature.

Figure 6 illustrates examples of these features.

Also, using continuous temperature logging data in depth, this program can estimate the formation temperature and/or recovery temperature at any elapsed time versus depth continuously. This means the true formation temperature profile and its reliability are plotted just after temperature recovery log has been run.

6. CONCLUSIONS

The true formation temperature is essentially important value for geothermal reservoir evaluation. Estimation of the true formation temperature with good accuracy using short period of logging time is preferable economically and help to make a quick decision, that is very important for the well drilling. Through these studies, we can conclude as follows:

1) The Curve-fitting method (CFM) as an estimation method of the true formation temperature has been successfully developed. CFM is based on mathematical model for temperature recovery and includes the inversion scheme with the non-liner least squares method. Because of these schemes, estimated temperature can be computed immediately after the temperature recovery log has been done.

2) In comparison with the Horner-plot method, CFM is more reliable and useful for the temperature recovery and the true formation temperature estimation.

3) The accuracy for the true formation temperature estimation is less than 5°C even using 24 hours temperature recovery data, according to our case studies.

4) Developed data acquisition system can give various parameters for decision making when the measurement of temperature recovery should be finished.

5) Through these case studies, it is expected to reduce the logging and rig costs using CFM as an estimation method of the true formation temperature and recovery temperature.

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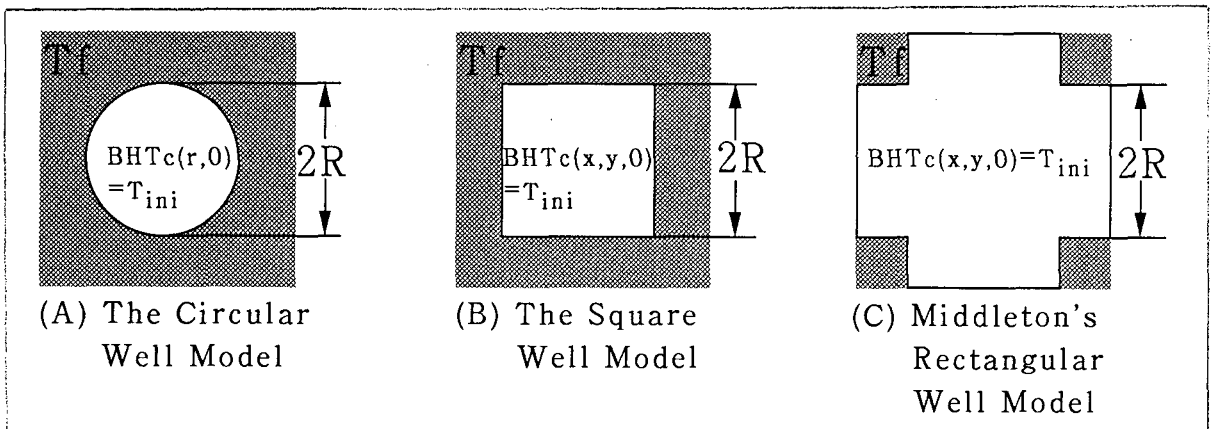

Figure 1. Physical well models as a mathematical model.

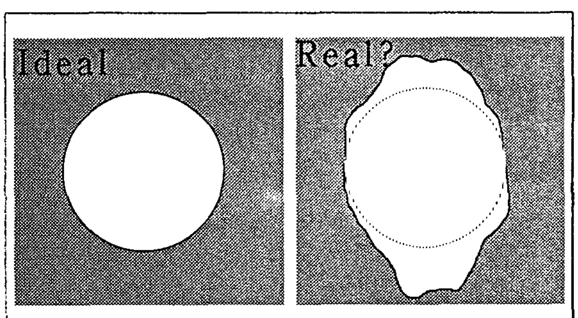

Figure 2. Schematic ideal and realistic wellbore configuration.

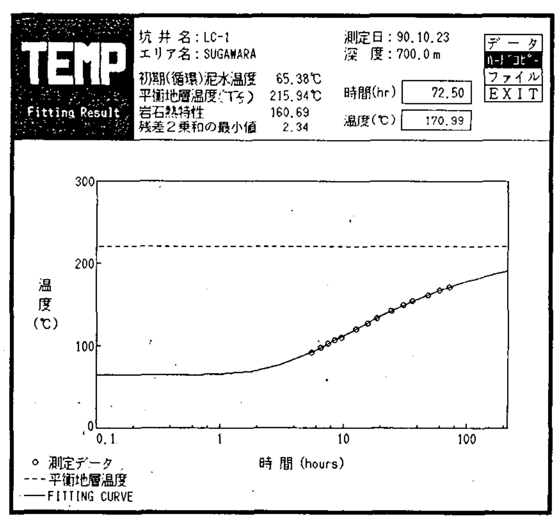

Figure 3. Example of curve–fitting with field data by the Curve–fitting method at 700 m depth of the LC–1 well.

Table 1. Accuracy of the Curve–fitting method depending upon number of data and log interval.

Elapsed Time (Hours)	①	②	③	④	⑤ − 1	⑤ − 2	⑤ − 3	⑤ − 4	⑥	⑦	⑧	⑨
5.5	92.0	92.0	92.0	92.0	92.0	92.0		92.0	92.0	92.0	92.0	92.0
6.5	98.5					98.5		98.5			98.5	
7.5	103.0	103.0	103.0	103.0	103.0	103.0					103.0	
8.5	107.4	107.4				107.4					107.4	107.4
9.5	110.4	110.4	110.4	110.4	110.4		110.4		110.4	110.4	110.4	
12.5	119.6	119.6	119.6				119.6				119.6	119.6
15.5	126.6	126.6	126.6	126.6	126.6		126.6	126.6	126.6		−	−
18.5	132.8	132.8	132.8	132.8			132.8	132.8			−	−
24.5	142.4	142.4	142.4	142.4	142.4	142.4	142.4	142.4	142.4	142.4	−	−
No. of Data	9	8	7	6	5	5	5	5	4	3	6	3
E.F.T(℃) for 72.5 hrs	170.5	170.4	171.2	170.7	171.2	169.1	174.9	172.4	172.0	171.5	159.7	160.9
E.F.T - TRUE for 72.5 hrs	−0.5	−0.6	+0.2	−0.3	+0.2	−1.9	+3.9	+1.4	+1.0	+0.5	-11.3	-10.1

E.F.T : Estimated Formation Temperature by Curve-Fitting Method
TRUE : Measured Temperature by Logging at 72.5 hours(170.9 degree C)

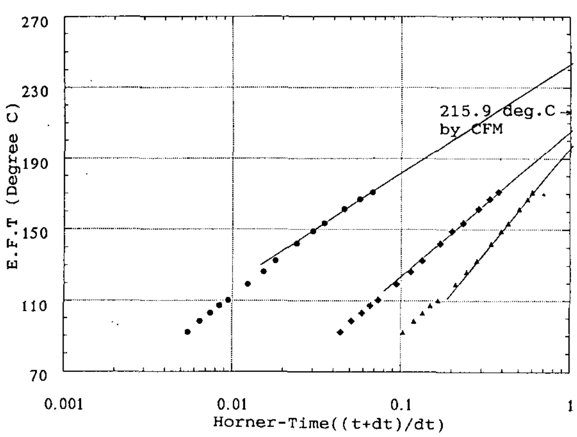

Figure 4. Example of estimation of the true formation temperature by the Horner–plot method.
These graphs show effects between the various circulation time at 700 m depth of the LC–1 well (Tffit = 215°C). C: Assumed circulation time is 40 days (Tfbuild = 243°C). S: Assumed circulation time is five days (Tfbuild = 205°C). T: Assumed circulation time is two days (Tfbuild = 196°C).

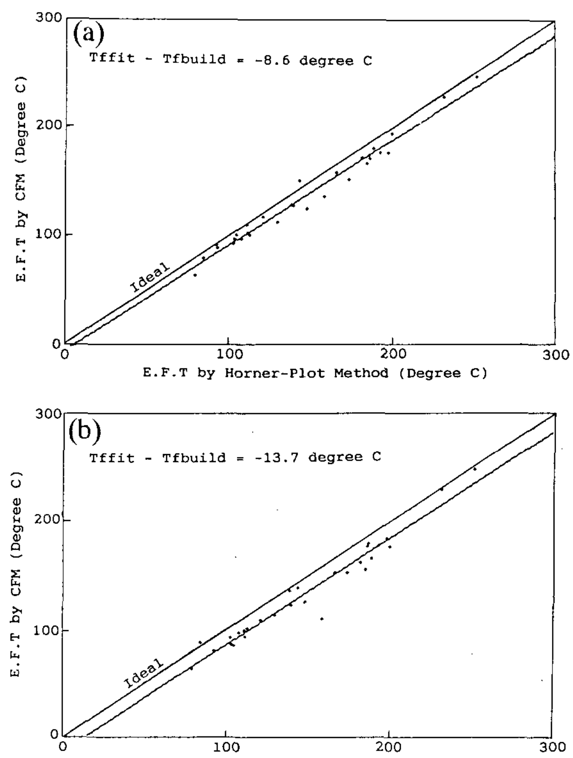

Figure 5. Cross–plot of estimated true temperature by the Horner–plot method versus CFM (a) using elapsed time of 120 hours and (b) using elapsed time of eight hours.

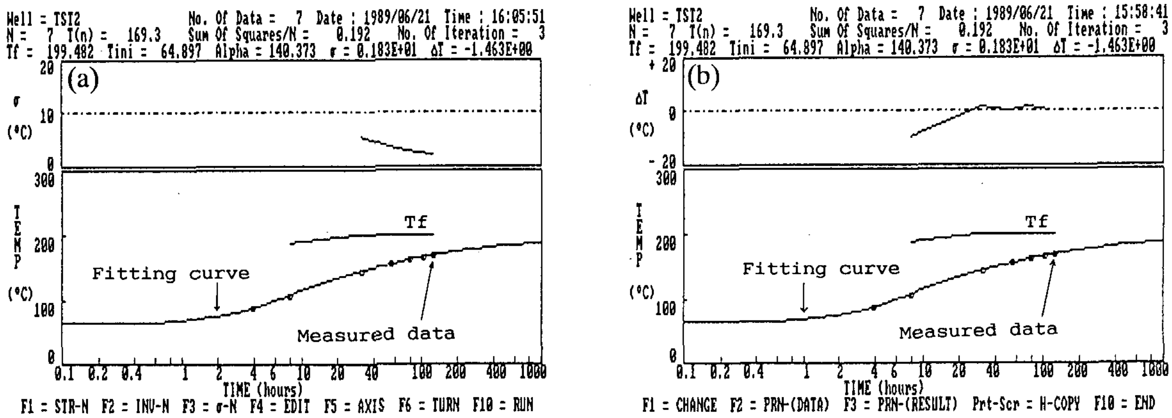

Figure 6. Example of parameters for evaluation of reliability of estimated temperatures. (a) Example of standard deviation of estimated temperatures. (b) Example of transition of estimated temperatures.