ESTIMATING OF EQUIBRIUM FORMATION TEMPERATURE BY CURVE FITTING METHOD

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1. Introduction

Determination of true formation temperature from measured bottom-hole temperature is important for geothermal reservoir evaluations after the completion of well drilling, and sometimes useful in selecting lost circulation materials for remedy work. However, the original temperature field around a borehole is disturbed by circulating mud during drilling, and it takes a considerably long time to reach temperature equilibrium between the formation and drilling mud after drilling and mud circulation has ended. The Horner-plot method has popularly been in use for estimating the formation temperature. But this method requires long-period temperature logging data up to about 120 hours to get the reliable estimation, particularly in case the geothermal gradient is relative high as in geothermal wells. Several mathematical models for bottom-hole temperature stabilization have been proposed for estimation of formation temperature from short-period logging data after cessation of circulation of drilling mud. These models have been applied to determine formation temperature using the curve-fitting method. Non-linear equation reduction by least squares solution has been successfully developed in the model proposed by Middleton (1979).

This study also represents some of the research achievements included in the "Research and Development of Lost Circulation Techniques in Geothermal Wells" that is part of the "Development of geothermal hot water power generation plant," an undertaking aided by the MITI Sunshine Project.

2. Mathematical temperature stabilization model

In studying the non-linear least squares fitting method, the model devised by Middleton (1979) was adopted. Middleton (1979) considered that a vertical cylinder of small radius could be approximated by a square cylinder in rectangular coordinates. Therefore, the temperature distribution BHTc (x, y, t), around a vertical cylinder of infinite length after cessation of mud circulation could be expressed as the following equation:

$$BHTc(x,y,t)=Tm+1/4(Tf-Tm)\{erfc(R-x/\tau)+erfc(R+x/\tau))X(erfc(R-y/\tau)+erfc(R+y/\tau)\} \quad \ldots\ldots\ldots (1)$$

where $\tau=(4Kt)^{1/2}$

$erfc(x)=2/\int_x^\infty exp(-t^2)dt$

Tm is the mud temperature in the borehole at the instant that circulation ceases, Tf is the formation equilibrium temperature, R is the effective radius of the region affected by drilling, K is the thermal diffusivity of the well contents, x, y are the Cartesian coordinates in the horizontal plane, and t is the shut-in time after the termination of mud circulation.

Assuming that the measurement is made at the center of the well (x=0, y=0), temperature becomes a function of time only:

$$BHTc(t)=Tm+(Tf-Tm)X\{erfc(R/(4Kt)^{1/2})\}^2 \quad \ldots\ldots\ldots (2)$$

As apparent from the above equation, knowledge of circulation time of the drilling fluids, which is required in the Horner-plot method of correction for borehole temperature disturbance, is not necessary in this model. The initial temperature distribution given by equation (1) is shown in Fig. 1.

3. Non-linear least squares fitting method

There are two methods of estimating formation temperature using mathematical models, one is a curve fitting technique, the other is a non-linear least squares fitting method. In a curve fitting technique, the formation temperature can be obtained by superimposing a set of master curves, based on equation (2), on observed data plotted at the same scale.

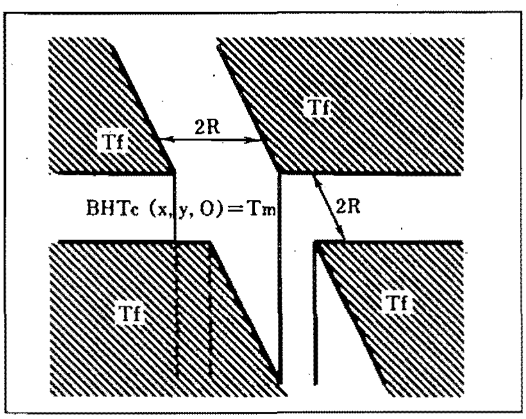


Fig. 1 Initial temperature distribution fr equation (1)

On the other hand, in a non-linear least squares fitting method, non-linear least squares method is applied to obtain the formation temperature.

$$S=\sum_{i=1}^{n}(BHTc(ti)-BHTo(ti))^2 \text{ ........ (3)}$$

where BHTc(ti) is the calculated value from equation (2), BHTo(ti) is the observed temperature data, and optimum values of Tf and Tm can be obtained by the mathematical inversion technique to minimize the value of S in equation (3).

Features of a non-linear least squares fitting method, in comparison with curve fitting technique, are in its rapidity and objectivity. Fig. 2 shows an example of the non-linear fitting result.

4. Results

In order to evaluate the reliability of non-linear least squares fitting method, a comparison between non-linear least squares fitting method and Horner-plot method, which was devised by Parasnis (1971), Dowdle and Cobb (1975), and Fertl and Winchmann (1977), has been made using temperature recovery test data obtained in five wells in Hohi geothermal field in Kyushu. Shown in Table 1 are the data of comparison between Tfbuild, formation temperature estimated by the dHorner-plot method, and Tffit, formation temperature estimated by the fitting method. In three wells out of the five wells -- A, C and E --, temperature logging had taken place at 128, 122 and 113 days respectively after cessation of circulation, so these observed results are shown as Tfobs, assuming they can be approximated to an equilibrium formation temperature.

According to this example, the average difference temperature among Tfbuild, Tffit and Tfobs is as follows:

(a) Average error between Tffit and Tfbuild ..... 11.3 deg. C
(b) Average error between Tffit and Tfobs ..... 5.5 deg. C
(c) Average error between Tfbuild and Tfobs ..... 7.9 deg. C

Assuming that Tfobs is the equilibrium formation temperature, non-linear least squares fitting method is found to suit the estimation of the formation temperature accurately enough compared with the Horner-plot method.

5. Discussion

Da-Xin (1986) pointed out the limits of the application of the fitting method because some parameters in equation (2), such as thermal diffusivity K and effective radius R, should be assumed to obtain the equilibrium formation temperature and this would cause large errors. Therefore, it is necessary to decide proper values of R and K, and to consider factors affecting on accuracy of fitting method.

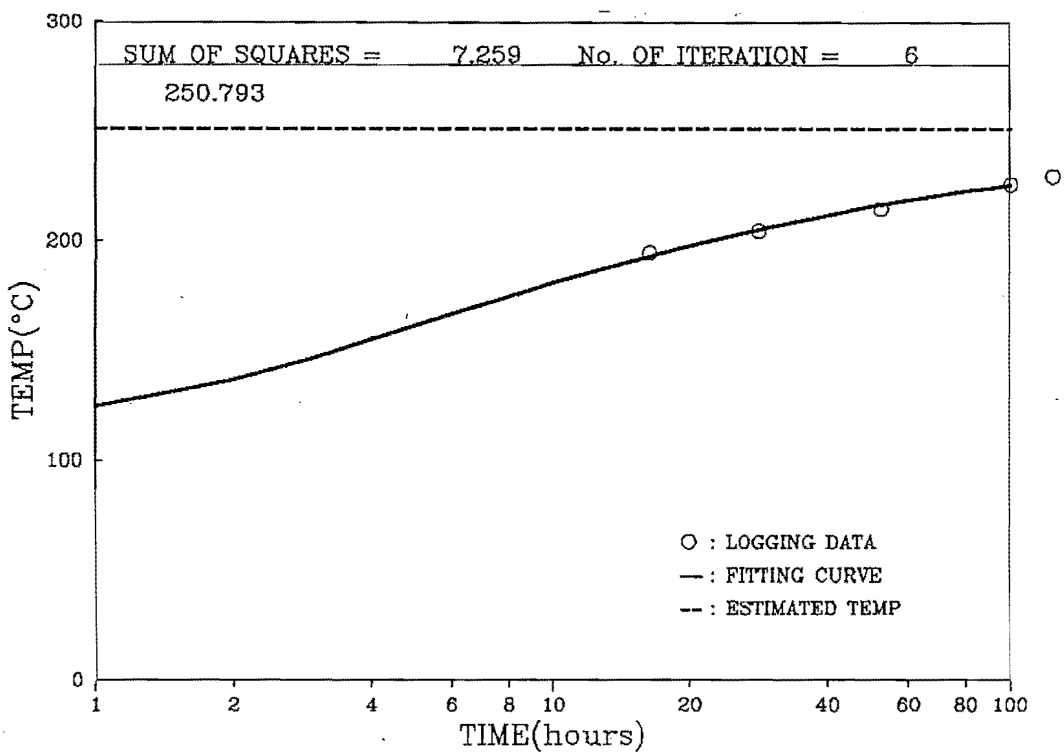


Fig. 2 Example of result by the non-linear least squares fitting method

(1) Effective radius R of the region affected by circulation
As shown in Fig. 1, Middleton's wellbore model seems to depart from an ideal cylindrical shape but this rectangular coordinates are better to describe the real geometrical configuration of the well, such as wash-out or caving of poorly consolidated formation.
Although other models, such as circular well proposed by Luikov (1968) or square well by Carslaw and Jaeger (1959), were derived and examined by Leblanc et al. (1981), Middleton's model would be appropriate if you use a half of bit size as an effective radius R.
(2) Thermal diffusivity K of well contents
Four important physical quantities to be considered in the thermal recovery problem are thermal conductivity $\lambda$, specific heat Cp, density $\rho$, and thermal diffusivity K. These quantities are related by following equation:

$$K=\lambda/\rho Cp \quad \text{......................} \quad (4)$$

There are three ways described below to determine the value of thermal diffusivity in applying fitting method.

(a) To use a typical assumed value of K, as Middleton (1978) or Leblanc (1981, 1982) did
(b) To use measured physical quantities using geological samples (cores or cuttings) to calculate the value of K.
(c) To handle K, in combination with R, as an inversion parameter in non-linear least square method in equation (3), as Da-Xin (1986) did.

While we adopted (b) in the latest analysis, Leblanc et al. (1982) empirically proposed 0.0035 $cm^2/sec$ as the value for thermal diffusivity under the curve fitting method.
Table 2 shows a comparison of estimated temperature between thermal diffusivity as calculated from core physical properties value and that as fixed at 0.0035 $cm^2/sec$ proposed by Leblanc.
Using thermal diffusivity as a fixed value is considered undesirable in terms of accuracy since thermal conductivity, among other rock physical properties, shows a wide range of values depending on the proportions of component minerals, the presence of metamorphosis, etc.
Knowledgement about thermal properties is needed for accurate estimation of formation temperature, but it is rare that the core samples can be obtained in normal drilling process. The method how to estimate rock thermal properties

Table 1 Comparison of estimated formation temperatures between non-linear fitting and Horner-plot method

| Well name (M. D.) | Depth (m) | Number of data | Tfbuild (℃) | Tffit (℃) | Tf obs (℃) |
|---|---|---|---|---|---|
| A (2,168 m) | 700 | 7 | 209 | 188 | 190 |
| | 1,500 | | 198 | 182 | 189 |
| | 1,600 | | 193 | 186 | 185 |
| | 1,700 | | 187 | 176 | 183 |
| B (2,402 m) | 2,200 | 7 | 184 | 170 | — |
| | 2,300 | | 193 | 182 | — |
| | 2,400 | | 200 | 205 | — |
| C (2,303 m) | 1,400 | 6 | 167 | 154 | 170 |
| | 2,000 | 4 | 199 | 183 | — |
| | 2,100 | | 201 | 186 | — |
| D (3,206 m) | 2,500 | 6 | 249 | 232 | — |
| | 3,000 | | 254 | 255 | — |
| | 3,200 | | 269 | 281 | — |
| E (3,003 m) | 2,600 | 5 | 250 | 251 | 255 |
| | 2,700 | | 254 | 261 | 262 |
| | 2,800 | | 259 | 269 | 267 |

Table 2 Effect of thermal diffusivity

| Well name | Depth (m) | Tf fit (℃) | | Tf obs |
|---|---|---|---|---|
| | | Measured value | Assumed value (K=0.0035) | |
| A | 700 | 188 (K=0.0086) | 231 | 190 |
| | 1,500 | 182 (K=0.0086) | 200 | 189 |
| | 1,600 | 180 (K=0.0086) | 197 | 185 |
| | 1,700 | 176 (K=0.0086) | 191 | 183 |
| C | 1,400 | 154 (K=0.0259) | 163 | 170 |
| E | 2,600 | 251 (K=0.0098) | 255 | 255 |
| | 2,700 | 261 (K=0.0098) | 265 | 262 |
| | 2,800 | 264 (K=0.0098) | 272 | 267 |
| Average error from Tf obs | | 5.5 ℃ | 10.9 ℃ | — |

without core samples has been derived based on statistical processing of measured data results of 255 core samples in 12 geothermal areas in Japan.

1) Thermal conductivity; $\lambda$

As mentioned before, the thermal conductivity of rocks shows no dependence on their kind, depth, etc. Therefore, the use of measurement data is considered indispensable with respect to thermal conductivity. Tanaka, Miyazawa, Hachino, Takasugi et al. (1988 not published yet) have reported measurement results of rock thermal conductivity from cuttings by the needle probe method. It is considered effective to apply this method as a simple and accurate process of measurement of thermal conductivity.

2) Density; $\rho$

Density is found dependent on depth in some kinds of rocks. Therefore, the rocks are classified broadly into five kinds, for each of which a correction formula is formed and employed.

3) Specific heat; Cp

Specific heat varies but little in value statistically, so a mean value (0.22 cal/g deg. C) is used as a fixed value.

(3) Temperature logging procedure

However, the temperature recovery data, used in verifying the non-linear least squares fitting technique, were presupposed to be analyzed by the Horner-plot method. Therefore, taking the following points into consideration in logging procedure would further improve the accuracy in estimated temperature by the fitting method.

1) More data in short-period

The non-linear least squares fitting technique, different from the Horner-plot method, is a theoretical method of solution, so improved accuracy is expected to result from an increased number of data in principle even if they are short-period ones.

Incidentally, Table 3 shows a comparison of the estimated temperature obtained by the use of all temperature recovery data and that obtained by the use of only the first two data.

The average error, from the formation equilibrium temperature Tfobs is not very great for estimation results from short-period and only two data. Estimating with this degree of accuracy would be impossible when a similar estimation were made by the Horner-plot method.

2) Correction for time lags during logging

Table 3 Accuracy of estimation with two short-period data

| Well name | Depth (m) | Tf fit (℃) | | Tf obs |
|---|---|---|---|---|
| | | Using all data | Using two data | |
| A | 700 | 188 (7 data) | 220 | 190 |
| | 1,500 | 182 (7 data) | 188 | 189 |
| | 1,600 | 180 (7 data) | 185 | 185 |
| | 1,700 | 176 (7 data) | 185 | 183 |
| C | 1,400 | 154 (6 data) | 147 | 170 |
| E | 2,600 | 251 (5 data) | 242 | 255 |
| | 2,700 | 261 (5 data) | 251 | 262 |
| | 2,800 | 264 (5 data) | 268 | 267 |
| Average error from Tf obs | | 5.5 ℃ | 10.1 ℃ | — |

When estimating the formation temperature from short-period logging data, it is necessary to determine the shut-in time as accurately as possible.

Correction was made in the latest analysis, too, since the cable speed and direction of logging (up/down survey) were definite.

Incidentally, it turned out in the latest example that an error of 5.4 deg. C on the average would occur by whether time lags were taken into consideration or not.

5. Conclusion

For estimating the formation temperature from short-period temperature logging data, it has turned out that the non-linear least squre fitting technique is applicable as a simple and relatively reliable method. It is necessary, however, that the thermal diffusivity of rocks, K, which is an important parameter, be determined as far as possible from the physical properties of cuttings of the formation in hand.

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