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Predicting Strata Temperature Distribution from Drilling Fluid Temperature

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ABSTRACT

Geothermal gradient is one of the most important parameters for geothermal exploration and exploitation. Mud is generally used as a drilling fluid in geothermal wells. According to energy conservation law, when the drilling penetrates through an aquifuge or aquitard, its temperature can be used to establish the mathematical analysis model for estimating the geothermal gradient. The recorded mud temperatures in some practical drilling cases in southwest China have been applied to study the influence radius of geotherm that is conducted by surrounding rock into the derived formula. The fitting calculation results show that the absolute error is generally very low, being less than 10%, which indicates that the proposed formula can be used to effectively predict the geothermal gradient. The calculation indicates that it is only when the rock conductive influencing radius is very small (around 0.25m) that it is possible to have a reasonable solution.

Keywords: Drilling fluid of mud, Geothermal gradient, Temperature, Energy conservation law, Rock conductive influencing radius.

1. INTRODUCTION

Geothermal resource is one of the newest sources of energy. It has recently gained considerable attention due to its renewable and clean characteristics. For the sake of energy conservation and to address the energy shortage, the exploitation and utilization of geothermal resources is becoming increasingly important, which leads to the reasonable utilization of geothermal resources to be an important strategic action that can alleviate the problems of resources shortages and environmental degradation [1-4].

Since geothermal energy has great potential for development and broad prospects for use, the realization of geothermal resources for sustainable development and utilization is a critical issue for the world's geothermal industry [5-14]. Scholars all over the world have done much research on the geothermal resources and hot springs, including studies on heat flow, the thermal state of the rock, the thermal structure of the Earth’s crust or upper mantle, the geothermal effects and climate change, mining geotherm, and other geothermal resources. [15-19]. Strata temperature, which is difficult to measure directly, is a key parameter in the research and development of underground hot water, the thermal storage to divide the drilling depth in the geothermal system, and the evaluation of the potential of geothermal resources. Currently, the geothermal temperature scale approach is an economical and effective means of providing this parameter. This approach has been widely used in estimating reservoir temperatures, including cationic, silica, gas chemistry, isotope, and so on [19-30].

The drilling fluid of mud, which can interfere with the temperature field near the borehole during the drilling process, is generally used in exploration and development of geothermal wells. When the drilling time is long enough to make the temperature balance with the surrounding rock, the surface temperature can reflect the actual status of the stratum temperature. Some related work has been done by Lachenbruch and Hrewer (1959), Albright (1976), Barelli and Palama (1981), and so on [31-37].

Geothermal gradient is one of the most important parameters for geothermal exploration and exploitation. In the drilling process, the effect of exchanging heat between the drilling fluid, which mainly consists of drilling mud, and the strata that surround the borehole will result in a distinct temperature increase in the circulated outflow fluid. If drilling penetrates through aquifuge or aquitard with a certain thickness, the drilling fluid will have almost no leakage, and the heat attracted from the surrounded strata will be mainly supplied by conduction. For a relatively constant fluid flowrate Q_l, the geothermal gradient can be calculated by energy conservation, and the reservoir temperature can be estimated resulting in a more reasonable drilling program being put forward.

2. DERIVATION OF THE CALCULATING EQUATION

The physical model of calculation is shown in Fig.1. When a borehole is drilled at a depth of H_w, for the given temperature of the inflow (T_0) and outflow drilling fluid (T_n), if the depth is divided into n parts evenly, the thickness of each part is:

$$z = H_w/n \tag{1}$$

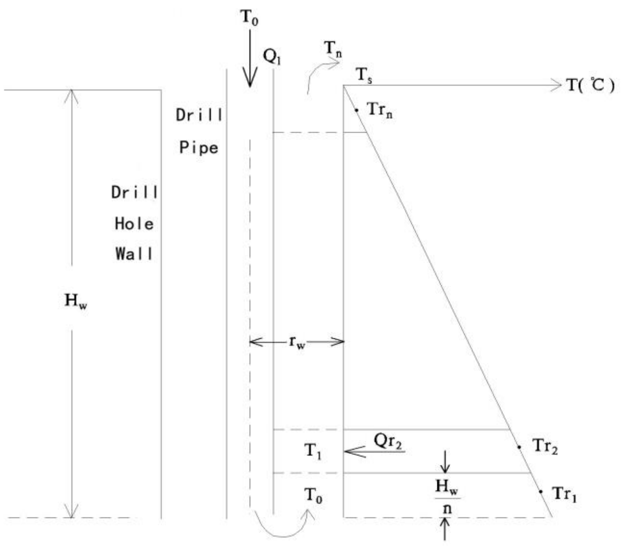

Figure 1. Model of drilling fluid temperature prediction of the reservoir temperature

Fig. 1 shows that the rising temperature in each part is obviously caused by the heat absorbed from the preceding part of the surrounding rock:

$$\begin{cases} C_l(T_1 - T_0)\rho_l Q_l = Q_{r1} \\ C_l(T_2 - T_1)\rho_l Q_l = Q_{r2} \\ C_l(T_3 - T_2)\rho_l Q_l = Q_{r3} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ C_l(T_n - T_{n-1})\rho_l Q_l = Q_{rn} \end{cases} \tag{2}$$

where C_l——specific heat of the drilling fluid, $KJ/(Kg\cdot{}^0C)$; ρ_l ——density of the drilling fluid, Kg/m^3; Q_l——constant fluid flowrate, m^3/s; Q_{r1}, Q_{r2}, $Q_{r3}\ldots Q_{rn}$——conductive heat flow from surrounding strata in different depth (upwards from bottom of borehole) (KJ/s);

T_0, T_1, T_2, ……T_{n-1}——temperature of the drilling fluid corresponding to the divided depth (${}^0C$).

According to the conductive equation, the heat flow that comes into the borehole from radial surrounding strata for a given divided depth can be described as:

$$Q_{ri} = -K_r(2\pi r\Delta z)\frac{dT}{dr}, i = 1、2、3......n \tag{3}$$

where K_r——surrounded rock conductivity, $W/(m\cdot k)$; r——the maximum distance that will cause heat flow from the surrounded strata while drilling, m; $\frac{dT}{dr}$ ——horizontal radial geothermal gradient at a given depth,${}^0C/m$; $2\pi r\Delta z$ ——the heat exchanging area between the drilling fluid and the surrounding strata at a given depth, m^2.

If the variable is separated and the integral transformation is used on equation (3) [38-39], the heat flow occurring at depth i can be derived as:

$$Q_{ri} = \frac{2\pi r_w K_r\left(T_{ri} - T_{i-1}\right)}{\ln\frac{R_i}{r_w}}\Delta z,\ \ i = 1、2、3......n \tag{4}$$

where T_{ri}——rock temperature of the divided depth i, ${}^0C$; r_w——borehole radius, m; R_i——rock conductive influencing radius of the divided depth i, m;

Combining equation (4) in equation (2) yields the following:

$$1000C_l(T_i - T_{i-1})\rho_l Q_l = Q_{ri} = \frac{2\pi r_w K_r\left(T_{ri} - T_{i-1}\right)}{\ln\frac{R_i}{r_w}}\Delta z \tag{5}$$

Or:

$$\frac{1000C_l\rho_l Q_l}{2\pi r_w K_r}\ln\frac{R_i}{r_w}\frac{T_i - T_{i-1}}{\Delta z} = T_{ri} - T_{i-1} \tag{6}$$

Equation (6) is high non-linear and remains hard to solve. However, when the drilling depths are divided into enough sections evenly, the thickness of each section is very small. The heat transfer in the upper and lower sections of the surrounding rock is approximately equal in scope, and the $\frac{R_i}{r_w}$ could be considered as a constant.

In this case, the following applies:

$$b = \frac{1000C_l\rho_l Q_l}{2\pi r_w K_r}\ln\frac{R_i}{r_w} \tag{7}$$

This parameter has length dimension. Thus, the equation (7) can be simplified as:

$$b\frac{T_i - T_{i-1}}{\Delta z} = T_{ri} - T_{i-1} \tag{8}$$

Take the temperature of drilling fluid with the depth as function T(z) (Coordinate of Z is positive downwards from the ground), and the surrounding rock temperature function as Tr(z), then equation (8) can be expressed as a differential equation:

$$-b\frac{dT}{dz} = T_r - T \tag{9}$$

Considering that geothermal growth is linear in the aquifuge, the gradient is fixed, as expressed by the following:

$$G(t)=\frac{\left(T_{ri}-T_{ri+1}\right)n}{H_w}\quad i=1,2,3......n-1 \tag{10}$$

Or:

$$T_r=T_s+G(t)z \tag{11}$$

G(t) is simplified as G. Combining equation (11) and equation (9) yields the following:

$$-b\frac{dT}{dz}=T_s+Gz-T \tag{12}$$

Its general solution is:

$$T=bG+(T_s+Gz)-C_0e^{z/b} \tag{13}$$

where C_0 is an undetermined constant. Making use of the surface temperature condition:

$$T(z=0)=T_n=bG+T_s-C_0 \tag{14}$$

Hence,

$$C_0=bG+T_s-T_n \tag{15}$$

Then, we have:

$$T(z)=bG+(T_s+Gz)-(T_s+bG-T_n)e^{z/b} \tag{16}$$

To determine the geothermal gradient G, the bottom hole temperature T_0 is inserted into equation (16), yielding the following:

$$T(z=H_w)=T_0=bG+(T_s+GH_w)-(T_s+bG-T_n)e^{H_w/b} \tag{17}$$

Namely, equation (17)can be changed to:

$$G=\frac{T_s+(T_n-T_s)\exp(H_w/b)-T_0}{b\exp(H_w/b)-(b+H_w)} \tag{18}$$

Integral constants can also be obtained by the bottom hole temperature T_0.

Note that we define:

$$C_0=\frac{bG+T_s+GH_w-T_0}{\exp(H_w/b)} \tag{19}$$

Yielding:

$$T(z)=bG+(T_s+Gz)-(T_s+bG+GH_w-T_0)e^{(z-H_w)/b} \tag{20}$$

Moreover, the above equation can be rewritten as:

$$T(z=0)=bG+T_s-(T_s+bG+GH_w-T_0)e^{-H_w/b} \tag{21}$$

The equation (16) and equation (20) are equivalent.

Table 1. The best-fit list for predicting geothermal gradient through the actual drilling mud

Arguments / Hole location	T_0	T_s	T_n	ρ_l (Kg /m^3)	Q_l (l/s)	C_l KJ/（Kg·^{0}C）	r_w	H_w	R_i	K_r W /(m·k)	Calculation $G(t)$	Actual measurement $G(t)$	Relative error (%)
	(^{0}C)						(m)				(^{0}C /m)		
Yunnan elderly activity center	23	17	31	1190	3.00	4.25	0.088	1382	0.25	2.4	0.030	0.028	7.14
Yunnan Tuodong sports center	22	17	31	1150	2.50	4.25	0.08	1285	0.25	2.4	0.034	0.033	3.03
Yunnan Yiliang city coal mining administration	20	17	23	1200	2.50	4.12	0.108	420	0.23	2.1	0.051	0.050	2.00
Kunming Lin Yuan real estate company	23	17	30	1100	2.50	4.25	0.108	801	0.25	2.8	0.049	0.045	8.89
Yunnan Xuanwei hot well	20	18	26	1070	2.50	4.25	0.108	1311	0.26	2.1	0.019	0.018	5.56
Yunnan Xundian County Beidaying pastures	22	17	24	1200	1.88	4.12	0.108	692	0.25	2.8	0.028	0.023	21.74
Guiyang Wudang District xiangzhigou scenic area	19	17	24	1200	2.50	4.12	0.076	1150	0.24	1.8	0.021	0.021	0
Kunming Haigeng sports training base	23	17	30	1150	2.00	4.26	0.108	720	0.25	2.5	0.055	0.051	7.20

3. PRACTICAL CASES

The mud temperatures in some actual drilling cases in southwest China were recorded to study the influence radius of geotherm that is conducted by surrounding rock. By using Excel spreadsheets, the related parameters from these boreholes have been input into the corresponding column, and comprehensive parameters (b) have been calculated according to equation (7). For each borehole, when different values for the influence radius of the surrounding rock's thermal conductivity in each well were given， the corresponding geothermal gradient G_i was calculated based on equation (19). By comparing the geothermal gradient value that was calculated with the actual measured temperature in each borehole, the best fitting data (Table 1) were determined. Since the friction heat generated during the drilling process is ignored in the formula derivation of the geothermal gradient, all the calculated values of geothermal gradient appear higher than the actual ones. Furthermore, the simulation is available only when the rock conductive influencing radius is very small (about 0.25m). This indicates that to form a stable heat flow field, the role of the surrounding rock in supplying heat for drilling mud is not essential. The simulation results show that the absolute error rate is generally low in the mass, and the relative error rate is less than 10%.

Setting 0.25m of the surrounding rock conductive influencing radius as the empirical value, we can predict the computation in the process of several drilling construction sites in Yunnan and Guizhou Provinces, in southwest China. Comparing the calculated value with the actual detected data of the final hole, the relative error rate is less than 10% (Table 2), which proves the derived formula is very practical.

Table 2. Comparison of the predicting geothermal gradient through several drilling mud sites in Yunnan and Guizhou Provinces with the actual measured value

Arguments / Hole location	T_0 (${}^0C$)	T_s	T_n	ρ_l (Kg/m^3)	Q_l (l/s)	C_l $KJ/(Kg\cdot{}^0C)$	r_w (m)	H_w (m)	K_r $W/(m\cdot k)$	Calculation $G(t)$ (${}^0C/m$)	Actual measurement $G(t)$	Relative error (%)
Guizhou Pingba County Xujiadu	22	17	21	1200	2.00	4.12	0.108	400	1.3	0.0103	0.0105	1.91
Yunnan Dali city haidong hot well	20	17	21	1180	1.67	4.26	0.076	760	2.4	0.0145	0.0135	6.89
Kunming New Asia sports city	21	17	25	1100	3.00	4.425	0.108	773	2.5	0.031	0.030	3.33
Yunnan Luoping county people's hospital	20	17	21	1180	2.00	4.26	0.076	860	1.8	0.0129	0.0124	3.88
Yunnan Yuxi cigarette factories filter rods factory	19	17	23	1180	2.00	4.12	0.108	660	1.9	0.0305	0.0279	8.52

4. CONCLUSIONS

(1) In the process of geothermal exploration, the drilling fluid of mud will extract heat from the surrounding rock when penetrating through aquifuge, which will inevitably result in a significant temperature increase in the outflow drilling fluid. Since the heat thoroughly transfers by conduction, Fourier law and energy conservation law can be employed to calculate the strata temperature.

(2) Once the parameters of the drilling mud fluid and the rock thermal conductivity are measured, the general derived formula $G = \dfrac{T_s + (T_n - T_s)\exp(H_w / b) - T_0}{b\exp(H_w / b) - (b + H_w)}$ can be used to estimate the geothermal gradient in the aquifuge.

(3) The fitting calculation results of the thermal influence radius, which is conducted and formed by surrounding rock, show that the relative error rate is less than 10% in some practical drilling cases in southwest China.

(4) Only when the rock conductive influencing radius is very small, it is possible to have a reasonable solution, which indicates that the role of the surrounding rock in supplying heat for drilling mud is not essential to form a stable state. The suggested value is around 0.25m empirically.

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