RECOVERY OF THE THERMAL EQUILIBRIUM IN DEEP AND SUPER DEEP WELLS: UTILIZATION OF MEASUREMENTS WHILE DRILLING DATA

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ABSTRACT

It is shown that in deep and super deep wells the temperature of the drilling fluid (at a given depth) depends on the current vertical depth, on drilling technology (flow rate, well design, fluid properties, penetration rate, etc.), geothermal gradient and thermal properties of the formation. It is demonstrated that minimum field data: records of stabilized outlet mud temperature, several values of bottom-hole mud temperature measured while drilling (MWD) are needed to construct an empirical equation which approximates the downhole temperature profile during drilling. An analytical equation is presented which describes recovery of the thermal equilibrium when the temperature of drilling fluid (at a given depth) is a linear function of time. Calculations of shut-in temperatures for two field examples are also presented.

INTRODUCTION

The modelling of primary oil production and design of enhanced oil recovery operations, well log interpretation, well drilling and completion operations, and evaluation of geothermal energy resources require knowledge of the undisturbed reservoir temperature. Temperature measurements in wells are mainly used to determine the temperature of the Earth's interior. The drilling process, however, greatly alters the temperature of the reservoir immediately surrounding the well. The temperature change is affected by the duration of drilling fluid circulation, the temperature difference between the reservoir and the drilling fluid, the well radius, the thermal diffusivity of the formations, and the drilling technology used. Given these factors, the exact determination of reservoir temperature at any depth requires a certain length of time in which the well is not in operation. In theory, this shut-in time is infinitely long. There is, however, a practical limit to the time required for the difference in temperature between the well wall and surrounding reservoir to become a specified small value.

The results of field and analytical investigations have shown that in many cases the effective temperature ($T_e$) of the circulating fluid (mud) at a given depth can be assumed constant during drilling or production (Lachenbruch and Brewer, 1959; Ramey, 1962; Edwardson et al., 1962; Jaeger, 1961; Kutasov et al., 1966; Raymond, 1969). Here we should to note that even for a continuous mud circulation process the wellbore temperature is dependent on the current well depth and other factors. The term “effective fluid temperature” is used to describe the temperature disturbance of formations while drilling. In their classical work Lachenbruch and Brewer (1959) have shown that the wellbore shut-in temperature mainly depends on the amount of thermal energy transferred to (or from) formations. While drilling deep sections of super deep wells, the penetration rates become small and the time of thermal disturbance increases. Below it will be shown that in deep wells the mud circulation temperature can be approximated as a linear time function. The objective of this paper is twofold: (a) to demonstrate how temperature measurements while drilling (MWD) can be utilized to determine the downhole drilling mud temperature profile, and, (b) how the MWD data can be used in estimation of the transient shut-in temperatures.

EMPIRICAL EQUATION

The temperature surveys in many deep wells have shown that both the outlet drilling fluid temperature and the bottom-hole temperature varies monotonically with the vertical depth (Fig. 1).
It was suggested (Kuliev et al., 1968) that the stabilized circulating fluid temperature in the annulus ($T_m$) at any point can be expressed as

$$T_m = A_0 + A_1 h + A_2 H,$$

where the values $A_0$, $A_1$, and $A_2$ are constants for a given area, $h$ is the current vertical depth and $H$ is the total vertical depth of the well (the position of the bottom of the drill pipe at fluid circulation). The values of $A_0$, $A_1$, and $A_2$ are dependent on drilling technology (flow rate, well design, fluid properties, penetration rate, etc.), geothermal gradient and thermal properties of the formation. It is assumed that, for the given area, the above mentioned parameters vary within narrow limits. In order to obtain the values of $A_0$, $A_1$, and $A_2$ the records of the outlet fluid (mud) temperature at $h = 0$ and results of downhole temperature surveys are needed. In Formula 1 the value of $T_m$ is the stabilized downhole circulating temperature. The time of the downhole temperature stabilization ($t_s$) can be estimated from the routinely recorded outlet mud temperature logs (Kutasov et al., 1988; Kutasov, 1999).

Eq. (1) was verified (Kutasov et al., 1988) with more than 10 deep wells, including two offshore wells, and the results were satisfactory ones. Here we are presenting two examples of applying Eq. (1) for prediction downhole circulating temperatures. It will be shown that only a minimum of field data is needed to use this empirical method.

**Mississippi well**

The results of field temperature surveys and additional data (Table 1) were taken from the paper of Wooley et al. (1984). Three measurements of stabilized bottom-hole circulating temperatures and three values of stabilized outlet mud temperatures were run in a multiple regression analysis computer program and the coefficients of the empirical Formula (1) were obtained

$$A_0 = 32.68^\circ C, \quad A_1 = 0.01685^\circ C/m, \quad A_2 = 0.003148^\circ C/m.$$

Thus, the equation for the downhole circulating temperature is

$$T_m = 32.68 + 0.01685h + 0.003148H.$$  \hspace{1cm} (2)

**Webb County, Texas**

The temperature measurements (Table 1) in this location were obtained from the paper of Venditto and George (1984). It was not known whether these measurements were taken in a single well or in the wells in the same area. But since this empirical method can be applied to an entire area as well as to a single well, the data points were used simultaneously to calculate the coefficients in formula (1). By using the multiple regression analysis computer program was obtained,

$$A_0 = 5.69^\circ C, \quad A_1 = 0.00636^\circ C/m,$$

![Figure 1: Well 12-PXC, Stavropol district, Russia (Proselkov, 1975). 1 - Geothermal curve, 2 - Circulating bottom-hole temperature, 3 - Outlet drilling mud temperature, 4 - Inlet drilling mud temperature](image)
Thus, the equation for the downhole circulating temperature is
\[ T_m = 5.69 + 0.00636 h + 0.01714 H. \] (3)

In Table 1 the measured and predicted values of bottom-hole and outlet circulating temperatures are compared and the agreement is seen to be good in both cases. The significant difference in values of \( A_o \), \( A_1 \), and \( A_2 \) for the Mississippi and the Texas wells indicates that these coefficients are valid only within a given area.

Let us assume that for the well section \((H - h)\) the penetration rate is constant \((u)\).

Then \( H = h + ut \) and taking into account Eq. (1):
\[ T_m = A_o + A_1 h + A_2 (h + ut), \] or
\[ T_m = B_o + B_1 t, \quad B_o = A_o + h(A_1 + A_2), \quad B_1 = A_2 u. \] (4)

Introducing the dimensionless circulation time \((t_D)\) we obtain

**CUMULATIVE HEAT FLOW**

**Constant drilling mud temperature**

As we mentioned earlier, the wellbore shut-in temperature mainly depends on the amount of thermal energy transferred to (or from) formations (Lachenbruch and Brewer, 1959). It is known that the cumulative heat flow from the wellbore per unit of length is given by:
\[ Q = 2\pi \rho c_p r_w^3 (T_w - T_f) Q_D(t_D), \] (6)

where \( T_w = T_m \) is the temperature of the drilling fluid (at a given depth), \( \rho \) is the density of formations, \( c \) is the specific heat of formations, \( r_w \) is the well radius, and \( Q_D \) is the dimensionless cumulative heat flow. The time dependent function \( Q_D \) can be can be obtained from the integral
\[ Q_D = \int_0^{t_B} q_D(t_D) dt_D, \] (7)

where \( q_D \) is the dimensionless heat flow rate. We found (Kutasov, 1987) that the dimensionless heat flow rate can be approximated by a semi-analytical equation:

\[ q_D = \frac{1}{\ln(1 + D \sqrt{t_D})}, \] (8)

\[ D = d + \frac{1}{\sqrt{t_D + b}}, \quad d = \frac{\pi}{2}; b = \frac{2}{2\sqrt{\pi} - \pi}; b = 4.9589. \] (9)

The dimensionless flow rate \((q_D)\) can be also determined by using the empirical Eq. (10) (Chiu and Thakur, 1991):
\[ q_D = \frac{1}{c_1 \ln(1 + c_2 \sqrt{t_D})}, \quad c_1 = 0.982, \quad c_2 = 1.81. \] (10)

Commercially available software Maple 7 (Waterloo Maple, 2001) was utilized to compute the integral \( Q_D \), where the function \( q_D \) is given by Eq. (10). It was found that

\[ Q_D(t_d) = -2\text{Ei}(1,-2u) - \text{Ei}(1,-1u) - 0.69315 \]
\[ - \left\{ c_1 c_2^2 \right\} \]
\[ u = \ln(1 + c_2 \sqrt{t_d}), \] (11)

where \( -\text{Ei}(1, -x) = \text{Ei}(+x) \) is the exponential integral of a positive argument. In Table 2 the values of \( Q_D \) computed by two numerical integration methods are compared. The agreement between values of \( Q_D \) calculated by these two methods is seen to be good.

**Table 2: Comparison of values of dimensionless cumulative heat flow rate for a well with constant bore-face temperature.** \( Q_D^* \) – (Van Everdingen and Hurst, 1949); \( Q_D \) – Eq. (11)

<table>
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<tr>
<th>( t_d )</th>
<th>( Q_D^* )</th>
<th>( Q )</th>
</tr>
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<td>2</td>
<td>0.2447E+01</td>
<td>0.2448E+01</td>
</tr>
<tr>
<td>3</td>
<td>0.3202E+01</td>
<td>0.3204E+01</td>
</tr>
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<td>5</td>
<td>0.4539E+01</td>
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<td>10</td>
<td>0.7411E+01</td>
<td>0.7411E+01</td>
</tr>
<tr>
<td>20</td>
<td>0.1232E+02</td>
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</tr>
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<td>0.2485E+02</td>
</tr>
<tr>
<td>100</td>
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<td>0.7579E+02</td>
<td>0.7555E+02</td>
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<tr>
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<td>0.1606E+03</td>
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<tr>
<td>1000</td>
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<td>0.2922E+03</td>
</tr>
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<td>0.5317E+03</td>
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<tr>
<td>5000</td>
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DRILLING MUD TEMPERATURE AS LINEAR TIME FUNCTION

When the drilling mud temperature can be approximated by a linear function (Eq. 4) the Duhamel integral can be used

\[
Q_D = \int_0^{t_a} \frac{d}{dt_D} Q_D (t_D - \lambda) d\lambda, \quad (12)
\]

where

\[
T_w = \frac{T_w}{T_o} = (1 + b t_D), \quad T_w (\lambda) = 1 + b \lambda,
\]

and \(Q_D\) is the dimensionless cumulative heat flow rate for a well with constant bore-face temperature. Utilization of Eq. (11) does not allow the integration of Duhamel Integral. For this reason we used a simple function (Eq. (13))

\[
Q_D = A t_D^c \quad (13)
\]

to approximate the results of a numerical solution (Van Everdingen and Hurst, 1949). A linear regression program was used to compute the coefficients \(A\) and \(c\) (Table 3).

<table>
<thead>
<tr>
<th>(t_D)</th>
<th>Number of points</th>
<th>(c)</th>
<th>(A)</th>
<th>(R, %)</th>
</tr>
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<tr>
<td>5-100</td>
<td>22</td>
<td>0.75361</td>
<td>1.3088</td>
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</tr>
<tr>
<td>100-400</td>
<td>15</td>
<td>0.82297</td>
<td>0.97022</td>
<td>0.05</td>
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<td>400-1000</td>
<td>25</td>
<td>0.85013</td>
<td>0.82569</td>
<td>0.01</td>
</tr>
<tr>
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<td>0.75935</td>
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</tr>
<tr>
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<td>21</td>
<td>0.87274</td>
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<td>41</td>
<td>0.88213</td>
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</table>

For \(t_D > 100\) with \(R = \Delta Q/Q < 1.5\%\) the values of coefficients \(c\) and \(a\) can be approximated by the following expressions:

\[
\begin{align*}
c &= 0.028704 \ln t_D + 0.65297, \\
b &= -0.148 \ln t_D + 1.837.
\end{align*} \quad (14)
\]

Now the integral (Eq. (12)) can be evaluated

\[
Q_D = A t_D^c [1 + bt_D - \frac{bt_D}{(c - 1)(c + 1)}], \quad c < 1. \quad (15)
\]

RADIUS OF THERMAL INFLUENCE

In theory the drilling process affects the temperature field of formations at very long radial distances. There is, however, a practical limit to the distance – the radius of thermal influence \(r_{in}\), where for a given circulation period \(t = t_c\) the temperature \(T(r, t)\) is practically equal to the geothermal temperature \(T_f\). To avoid uncertainty, however, it is essential that the parameter \(r_{in}\) must not to be dependent on the temperature difference \(T(r, t) - T_f\). For this reason we used the thermal balance method to calculate the radius of thermal influence.

The results of modeling, experimental works, and field observations have shown the temperature distribution around the wellbore during drilling can be approximated by the following relation (Kutasov, 1968; Kutasov, 1976):

\[
\frac{T(r, t) - T_f}{T_w - T_f} = 1 - \frac{\ln r/r_w}{\ln r_{in}/r_w}, \quad r_w \leq r \leq r_{in}. \quad (16)
\]

Introducing the dimensionless values of circulation time, radial distance, radius of thermal influence, and temperature

\[
t_D = \frac{at_r}{r_w}, \quad r_D = \frac{r}{r_w}, \quad R_{in} = \frac{r_{in}}{r_w}, \quad T_D (r_D, t_D) = \frac{T(r, t) - T_f}{T_w - T_f},
\]

we obtain

\[
T_D (r_D, t_D) = 1 - \frac{\ln r_D}{\ln R_{in}}, \quad 1 \leq r_D \leq R_{in}. \quad (18)
\]

The dimensionless cumulative heat flow per unit of length is given by:

\[
Q_D = \int_0^{t_a} q_D dt_D = \int_1^{r_w} T_D (r_D, t_D) r_D dr_D. \quad (19)
\]

The last integral is evaluated by using the table for the following integral (Gradshtein and Ryzhik, 1965):

\[
\int x^n \ln x \ dx = x^{n+1} \left( \ln x - \frac{1}{n+1} \right). \quad (20)
\]

From Eqs. (18) – (20) we obtain

\[
Q_D = \frac{R_{in}^2 - 1}{4 \ln R_{in}} - \frac{1}{2}. \quad (21)
\]

By equating values of \(Q_D\) and \(Q_D\) (Eqs. (15) and (21)) we obtain a function \(R_{in} = f(t_D)\) which can be used to determine the dimensionless radius of thermal influence

\[
A t_D^c [1 + bt_D - \frac{bt_D}{(c - 1)(c + 1)}] = \frac{1}{4} \frac{R_{in}^2 - 2 \ln(R_{in}) - 1}{\ln(R_{in})}. \quad (22)
\]
SHUT-IN TEMPERATURE

Thus, for the moment of time \( t = t_c \), the temperature distribution in and around the wellbore is

\[
\begin{align*}
T_{wf} &= T_m = B_o + B_1 t_c, \quad 0 \leq r_D \leq 1, \\
T(t_c, r), \quad 1 \leq r_D \leq R_m, \\
T_f, \quad r_D > R_m.
\end{align*}
\] (23)

For the temperature distribution (Eq. (23)) we obtained the following formula for the wellbore shut-in temperature \( T_s \) (Kutasov, 1999):

\[
\frac{T_s(t_c,0) - B_o - B_1 t_c}{T_f - B_o - B_1 t_c} = \frac{Ei[-p(R_m)^2] - Ei(-p)}{2 \ln R_m},
\] (24)

\[
p = \frac{1}{4 n_D}, \quad n = \frac{t_f}{t_c},
\]

\[
T_f = \frac{2(T_s - B_o - B_1 t_c) \ln R_m}{Ei[-p(R_m)^2] - Ei(-p)} + B_o + B_1 t_c.
\] (25)

Hence, when the values of \( B_o \) and \( B_1 \) are known, only one value of shut-in temperature \( T_s \) is needed to determine the undisturbed formation temperature \( T_f \).

The derivation of Eq. (24) assumes that the difference in thermal properties of drilling mud and formations can be neglected. Although this is a conventional assumption even for interpreting bottom-hole temperature surveys (Timko and Fertl, 1972; Dowdle and Cobb, 1975), when the circulation periods are small, Eq. (24) should be used with caution for very small shut-in times.

FIELD EXAMPLES

Mississippi well (Wooley et al., 1984)

50 days were spent to drill the 6,534–7,214 m section of this well. Thus the average penetration was \( u = 0.566 \) m/hr and the values of \( B_1 \) and \( B_o \) were estimated (see Eq. (4)):

\[
B_1 = 0.001783 \degree C/hr, \quad B_o = 163.6 \degree C.
\]

The undisturbed temperature of formations at \( h = 6,534 \) m is \( T_f = 187.8 \degree C \). The average temperature of the drilling mud at this depth is \( T_m = 163.6 \degree C \) (Eq. 2).

The radius of thermal influence was computed from Eq. (22).

In Table 4 we present results of calculations after Eq. (24) values of \( \Delta T = T_f - T_s \). We also consider the case when the average temperature of the drilling mud (during the circulation period) is used at calculations of \( \Delta T \). For the Well # 30 we present results of calculations when the penetration rate was increased in three times (\( u = 1.7 \) m/hr). In this case \( t_c = 359 \) hrs and \( B_1 = 0.02971 \degree C/hr \) (Table 4).

From the last Table follows that for large shut-in times the average drilling mud temperature (case when \( B_1 = 0 \)) can be used to estimate the function \( \Delta T = f(t_c) \).

CONCLUSIONS

It is demonstrated that in deep wells a simple empirical formula approximates the downhole temperature profile during drilling. It is shown that this formula can be combined with an analytical solution and then only one shut-in temperature log is required to estimate the undisturbed (static) formation temperature.

REFERENCES


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