Journal of Petroleum and Gas Engineering Vol. 1(1), pp. 001-008, March 2010
Available online at http://www.academicjournals.org/JPGE

Full Length Research Paper

A new method for determining the formation temperature from bottom-hole temperature logs

I. M. Kutasov[1] **and L.V. Eppelbaum**[2]*

[1]Pajarito Enterprises, 640 Alta Vista, Suite 124, Santa Fe, New Mexico 87505, USA.
[2]Department of Geophysics and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Ramat Aviv 69978, Tel Aviv, Israel.

Accepted 27 January, 2010

Earlier, the authors proposed a new method for prediction of formation temperatures in permafrost regions from temperature logs in deep wells, and developed working formulas to process field data. The application of the proposed method on predicting the undisturbed formation temperature does not depend: (a) on the well drilling history (vertical depth versus time and stops in mud circulation), (b) on the knowledge of thermal diffusivity of formations and well radius. This method is based on using only three values of shut-in temperatures. Our investigation indicates that for bottom-hole temperature (BHT) tests, where the thermal disturbance of formations is caused mainly by one short (3-24 hours) continuous drilling fluid circulation period, the developed earlier method can be utilized for processing results of BHT surveys. The results of bottom-hole temperature surveys in three wells and data for one simulated example were used to validate our proposal. We suggest that application of this procedure in oil and gas industry will increase the reliability of temperature field BHT tests.

Key words: Formation temperature, bottom-hole temperature logs, generalized Horner method, oil and gas industry.

INTRODUCTION

It is known that temperature field investigations play an important role by prospecting and exploitation of oil and gas deposits (Melton and Gardini, 1984; Deming and Chapman, 1988; Eppelbaum et al., 1996; Kutasov, 1999; McAleese, 2000; Andaverde et al., 2005; Waples et al., 2004; Zschocke, 2005; Verma et al., 2006; Pasquale et al., 2008, etc.).

The determination of physical properties of reservoir fluids, calculation of hydrocarbon volumes (estimation of oil and gas formation volume factors, gas solubility), predictions of the gas hydrate prone zones, well log interpretation, determination of heat flow density and evaluation of geothermal energy resources require knowledge of the undisturbed formation temperature. In most cases, bottom-hole temperature surveys are mainly used to determine the temperature of the earth's interior. The drilling process, however, greatly alters the temperature of formation 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 reservoir and the drilling technology used. Given these factors, the exact determination of formation 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 to reach the original condition. 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 objective of this paper is to suggest a new approach for utilizing bottom-hole temperature logs in deep wells.

It should be noted that Horner method for obtaining the formation equilibrium temperature from the bottom-hole temperature is widely applied in oil and gas industry (Cao et al., 1988; Deming and Chapman, 1988; Kutasov, 1989; Nielsen et al., 1990; Kutasov, 1999; Mcaleese, 2000; Förster, 2001; Andaverde et al., 2005; Kutasov and Eppelbaum, 2005; Zschocke, 2005; Verma et al., 2006; Pasquale et al., 2008; Espinosa-Paredes et al., 2009). Earlier we proposed a new method for predicting the

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*Corresponding author. E-mail: levap@post.tau.ac.il. Fax: +972 3 6409282.

formation temperatures in permafrost regions from temperature logs in deep wells (Kutasov and Eppelbaum, 2003). The main features of the suggested method were the following:

1. In the permafrost section of the well, the starting point in the well thermal recovery is moved from the end of well completion to the moment of time when the refreezing of formations was completed. It is taken into account that the refreezing of thawed formations occurs in some temperature interval,
2. Below the permafrost base the starting point in the well thermal recovery is moved from the end of well completion to the moment of time when the first shut-in temperature log was taken.

The application of the proposed method of predicting the undisturbed formation temperature does not depend on the well drilling history (vertical depth versus time, stops in mud circulation). Specification of two parameters: thermal diffusivity of formations and well radius are not needed to compute the value of the undisturbed formation temperature (Kutasov and Eppelbaum, 2003). At conducting bottom-hole temperature logs, the thermal disturbance of formations (near the well's bottom) is caused mainly by one short continuous drilling fluid circulation period (prior to logging). The duration of this period usually consists of 3 - 24 h. As it is shown in this paper, the earlier suggested method (Kutasov and Eppelbaum, 2003) can be extended for determining the formation temperature from bottom-hole temperature surveys. Three field cases and one synthetic example are used to demonstrate the validity of this approach. The results of calculations are compared with those obtained after the Generalized Horner Method (GHM), where the values of well radius and formation diffusivity should be specified.

NEW METHOD (NM) AND WORKING FORMULA

Theoretically, 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 $T(r_{in}, t_c)$ is "practically" equal to the geothermal temperature T_f. To avoid this uncertainty, it is essential that the parameter r_{in} must not depend on the temperature difference $T(r_{in}, t_c) - T_f$. For this reason, we used the thermal balance method to calculate the radius of thermal influence. The results of modelling, experimental works and field observations indicate that the following relation could be used for approximating the temperature distribution around the wellbore during drilling (Kutasov, 1968, 1999). Let us assume that three shut-in temperatures T_{s1}, T_{s2}, and T_{s3} are measured at a given depth. We can consider that the period of time $t_c^* = t_c + t_{s1}$ as a new "thermal disturbance" period. Then the "shut-in times" are

$$t_{s1}^* = t_{s2} - t_{s1}, \quad t_{s2}^* = t_{s3} - t_{s1}. \tag{1}$$

Now dimensionless temperature distribution at $t = t_{s1}$ (Figure 1)

$$\left.\begin{cases} T_{cD}^*(r_D,\, t_{xD}) = 1, & 0 \le r_D \le 1, \\ T_{cD}^*(r_D,\, t_{xD}) = 1 - \ln r_D / \ln R_x, & 1 \le r_D \le R_x \\ T_{cD}^*(r_D,\, t_{xD}) = 0, & r_D > R_x. \end{cases}\right\}, \tag{2}$$

$$R_x = 1 + 2.184\sqrt{t_{xD}}, \qquad t_{xD} = \frac{a\, t_c^*}{r_{wx}^2}, \qquad R_x = \frac{r_{ix}}{r_{wx}}, \tag{3}$$

$$T_{cD}^*(r_D,\, t_{xD}) = \frac{T_c(r,t) - T_f}{T_{s1} - T_f}, \qquad r_D = \frac{r}{r_{wx}}, \tag{4}$$

Where; r_{wx} is the radius of a cylindrical source with a constant wall temperature (T_{s1}) during the thermal disturbance period (t_c^*), a is the thermal diffusivity of formations, t_c is the duration of the circulation period (at the bottom-hole), T_f is the undisturbed temperature of formations and r_{ix} is the radius of thermal influence. For the initial radial temperature distributions (equation 2) the dimensionless shut-in wellbore temperature (at $t_s > t_{s1}$) was presented earlier (Kritikos and Kutasov, 1988; Kutasov, 1999):

$$T_{sD}^* = \frac{T(0, t_s^*) - T_f}{T_{s1} - T_f} = 1 - \frac{Ei(-p^* R_x^2) - Ei(-p^*)}{2 \ln R_x}, \tag{5}$$

Where;

$$p^* = \frac{1}{4 n^* t_{xD}}, \quad n^* = \frac{t_s^*}{t_c^*}. \tag{6}$$

By using measurements T_{s2}, T_{s3} and equation (5) we can eliminate the formation temperature T_f. After simple transformations we obtain (Kutasov and Eppelbaum, 2003)

$$\gamma = \frac{T_{s2} - T_{s1}}{T_{s3} - T_{s1}} = \frac{Ei(-p_1^* R_x^2) - Ei(-p_1^*)}{Ei(-p_2^* R_x^2) - Ei(-p_2^*)}, \tag{7}$$

Where;

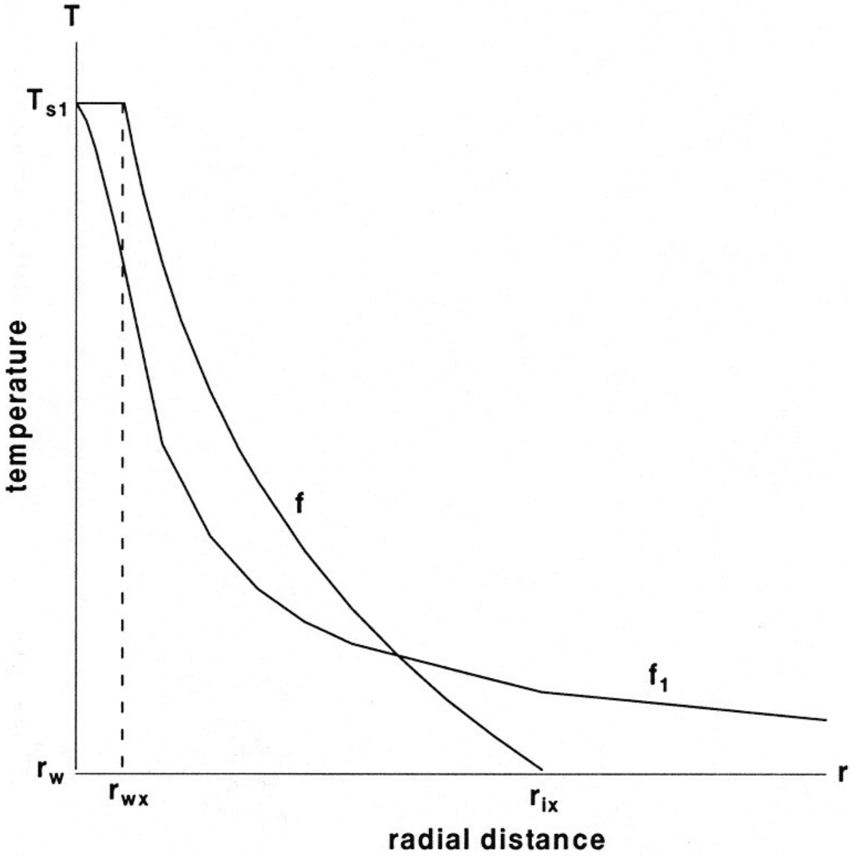

Figure 1. Actual (curve f_1) and assumed (curve f) radial temperature distributions at $t_s = t_{s1}$ – schematic curves.

$$p_1^* = \frac{1}{4n_1^* t_{xD}}, \qquad n_1^* = \frac{t_{s1}^*}{t_c^*}, \qquad p_2^* = \frac{1}{4n_2^* t_{xD}}, \qquad n_2^* = \frac{t_{s2}^*}{t_c^*}. \tag{8}$$

Substituting the value of R_x Formula (3) into Equation (7) we can obtain a formula for calculating the dimensionless disturbance time, t_{xD}, after this is possible to determine values of T_f, R_x, and $A = a_f / (r_{wx})^2$. Although the equation (7) is based on an analytical solution (Equation 6), we should mention several limitations in application of the suggested method. Firstly, the temperature ratio γ (Formula 7) should be determined with a high accuracy. This means that high accuracy of temperature measurements (T_{s1}, T_{s2}, T_{s3}) is needed. The temperature differences T_{s2} - T_{s1} and T_{s3} - T_{s1} should be significantly larger than the absolute accuracy of temperature measurements.

GENERALIZED HORNER METHOD (GHM)

Field investigations have shown that the bottom-hole circulating (without penetration) fluid temperature after some stabilization time can be considered constant (Figures 2 and 3). The solid curves in Figure 2 illustrate the calculated circulating mud temperatures (at a constant heat transfer coefficient) by using the Raymond (1969) model.

It was shown that by using the adjusted circulation time concept (Kutasov, 1987, 1989) a well with a constant borehole wall temperature can be substituted by a cylindrical source with a constant heat flow rate. Let us assume that at a given depth the fluid circulation started at the moment of time t = 0 and stopped at t = t_c. The corresponding values of the flow rates are

$$q(t = 0) = \infty, \qquad q(t = t_c) = q.$$

Using the adjusted circulation time concept and the principle of superposition for a well as a cylindrical source with a constant heat flow rate $q = q(t_c)$ which operates during the time $t = G{\cdot}t_c$ and shut-in thereafter, we obtained a working formula for processing field data (Kutasov and Eppelbaum, 2005):

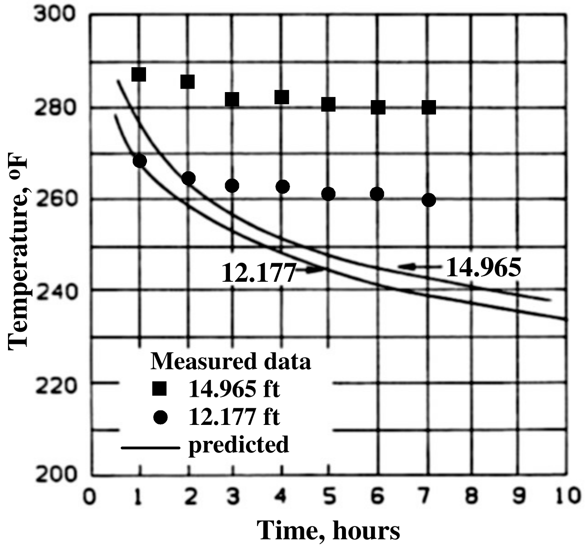

Figure 2. Comparison of measured and predicted circulating mud temperatures, Well 1 (Sump and Williams, 1973).

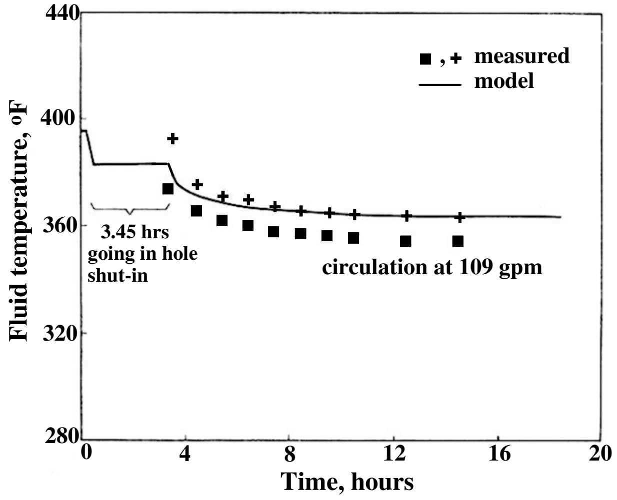

Figure 3. Circulating mud temperature at 23,669 ft (7214 m) – Mississippi well (Wooley et al., 1984).
Courtesy of Society of Petroleum Engineers.

$$T(r_w, t_s) = T_i + m \ln X, \quad m = \frac{q}{2\pi\lambda}, \tag{9}$$

$$X = \frac{1 + \left(c - \dfrac{1}{a + \sqrt{Gt_{cD} + t_{sD}}}\right)\sqrt{Gt_{cD} + t_{sD}}}{1 + \left(c - \dfrac{1}{a + \sqrt{t_{sD}}}\right)\sqrt{t_{sD}}}, \tag{10}$$

$$a = 2.7010505, \qquad c = 1.4986055,$$

$$\left\{\begin{matrix} G = 1 + \dfrac{1}{1 + AF}, & t_{cD} \le 10 \\ F = [\ln(1 + t_{cD})]^n, & n = 2/3 \quad A = 7/8 \end{matrix}\right\}, \tag{11}$$

$$G = \frac{\ln t_{cD} - \exp\left(-0.236\sqrt{t_{cD}}\right)}{\ln t_{cD} - 1}, \qquad t_{cD} > 10. \tag{12}$$

The correlation coefficient $G(t_{cD})$ varies in the narrow limits: $G(0) = 2$ and $G(\infty) = 1$ As can be seen from equation (9), the field data processing (semilog linear log) is similar to that of the Horner method. For this reason, we have given the name "Generalized Horner Method" to this procedure for determining the static temperature of formations. To calculate the ratio X, the thermal diffusivity of formations (a) should be determined with a reasonable accuracy. An example showing the effect of variation of this parameter on the accuracy of determining undisturbed formation temperature was presented in (Kutasov and Eppelbaum, 2005). It is easy to see that for large values of t_{cD} ($G \rightarrow 1$) and t_{sD} we obtain the well-known Horner equation (13).

$$T_s(r_w, t_s) = T_i + M \ln\left(\frac{t_s + t_c}{t_s}\right), \qquad M = \frac{m}{2} = \frac{q}{4\pi\lambda}. \tag{13}$$

FIELD EXAMPLES AND SYNTHETIC EXAMPLE

Field examples

We utilized the temperature data from Wells HL31 (depth 1,780 m) and HL30 (depth 1,394 m) (Andaverde et al., 2005). The third example is from Kelley Hot Springs geothermal reservoir, Moduc County, California (depth 1,035 m) (Roux et al., 1980).

Synthetic example

This example was taken from (Cao et al., 1980). We used in our calculations 8 points (from 15) and the assumed formation temperature was 120℃. The input data for 3 field cases and one synthetic example are presented in Tables 1 and 2.

Results of computations

Results of determinations of formation temperatures and some parameters by using the new method (equation (7)) are presented in Table 3. For comparison, we conducted calculations after formula (9) (Generalized Horner Method). The results of calculations are presented in Table 4. Comparing computed values of T_f (Table 5)

Table 1. Input data – Field cases.

Run number	t_{s1}, (h)	t_{s2}, (h)	t_{s3}, (h)	T_{s1}, (°C)	T_{s2}, (°C)	T_{s3}, (°C)
	Andaverde et al. (2005), HI31, t_c = 2.5 h					
1	6	12	18	186.3	206.9	219.0
2	6	12	24	186.3	206.9	231.9
3	6	12	30	186.3	206.9	239.8
4	6	12	36	186.3	206.9	247.7
5	12	18	24	206.9	219.0	231.9
6	12	18	30	206.9	219.0	239.8
7	12	18	36	206.9	219.0	247.7
8	18	24	30	219.0	231.9	239.8
9	18	24	36	219.0	231.9	247.7
10	24	30.	36	231.9	239.8	247.7
	Andaverde et al. (2005), HI30, t_c = 2.5 h					
11	6	12	18	178.6	198.9	211.4
12	6	12	24	178.6	198.9	225.8
13	6	12	30	178.6	198.9	235.1
14	6	12	36	178.6	198.9	240.4
15	6	12	42	178.6	198.9	247.1
16	12	18	24	198.9	211.4	225.8
17	12	18	30	198.9	211.4	235.1
18	12	18	36	198.9	211.4	240.4
19	12	18	42	198.9	211.4	247.1
20	18	24	30	211.4	225.8	235.1
21	18	24	36	211.4	225.8	240.4
22	18	24	42	211.4	225.8	247.1
23	24	30	36	225.8	235.1	240.4
24	24	30	42	225.8	235.1	247
	Roax et al. (1988), t_c = 12.0 h					
25	14.3	22.3	29.3	83.9	90.0	94.4

Table 2. Input data – synthetic example.

Run number	t_{s1}, (h)	T_{S2}, (h)	t_{s3}, (h)	T_{s1}, (°C)	T_{s2}, (°C)	T_{s3}, (°C)
	Cao et al. (1980), t_c = 5.0 h					
26	2	6	10	91.7	102.4	107.9
27	2	6	14	91.7	102.4	111.3
28	2	6	18	91.7	102.4	113.6
29	2	6	22	91.7	102.4	115.2
30	2	6	30	91.7	102.4	117.1
31	2	6	50	91.7	102.4	119.1
32	6	10	14	102.4	107.9	111.3
33	6	10	18	102.4	107.9	113.6
34	6	10	22	102.4	107.9	115.2
35	6	10	30	102.4	107.9	117.1
36	6	10	50	102.4	107.9	119.1
37	10	14	18	107.9	111.3	113.6
38	10	14	22	107.9	111.3	115.2
39	10	14	30	107.9	111.3	117.1
40	10	14	50	107.9	111.3	119.1

Table 2. Contd.

41	14	18	22	111.3	113.6	115.2
42	14	18	30	111.3	113.6	117.1
43	14	18	50	111.3	113.6	119.1
44	18	22	30	113.6	115.2	117.1
45	18	22	50	113.6	115.2	119.1
46	22	30	50	115.2	117.1	119.1

Table 3. Results of computations after Equations (3), (5) and (7)

t_{xD}	A,(1/h)	R_x	T_f, (°C)	t_{xD}	A (1/hr)	R_x	T_f, (°C)
Andaverde et al. (2005), HI31, t_c = 2.5 h				**Roax et al. (1988), t_c = 12.0 h**			
1.07	0.125	3.26	245.3	1.80	0.068	3.93	111.0
0.73	0.086	2.86	261.9	**Cao et al. (1980), t_c = 5.0 h**			
0.68	0.079	2.79	266.5	1.71	0.245	3.86	120.0
0.61	0.072	2.71	273.2	1.57	0.225	3.74	121.1
0.90	0.062	3.07	276.1	1.50	0.214	3.67	121.9
0.92	0.064	3.10	274.0	1.46	0.209	3.64	122.3
0.85	0.059	3.02	279.7	1.44	0.206	3.62	122.5
2.81	0.137	4.66	263.3	1.45	0.207	3.63	122.4
2.05	0.100	4.13	273.2	2.18	0.198	4.22	120.7
1.82	0.069	3.94	280.4	2.01	0.183	4.10	121.5
				1.94	0.176	4.04	122.0
Andaverde et al. (2005), HI30, t_c = 2.5 h				1.90	0.173	4.01	122.2
1.00	0.117	3.18	239.1	1.91	0.173	4.02	122.2
0.66	0.077	2.77	259.3	2.65	0.177	4.56	121.0
0.60	0.071	2.69	265.8	2.48	0.166	4.44	121.6
0.59	0.070	2.68	266.7	2.41	0.161	4.39	121.8
0.56	0.065	2.63	271.9	2.40	0.160	4.38	121.9
0.82	0.056	2.97	277.4	3.25	0.171	4.93	120.9
0.83	0.057	2.99	275.8	3.03	0.160	4.80	121.4
0.87	0.060	3.04	272.4	2.93	0.154	4.74	121.6
0.82	0.057	2.98	277.0	3.74	0.162	5.22	120.9
2.58	0.126	4.51	263.4	3.40	0.148	5.03	121.4
2.67	0.130	4.57	262.4	3.02	0.112	4.79	121.4
2.17	0.106	4.22	269.5				
4.16	0.157	5.45	257.4				
2.53	0.095	4.47	269.1				

shows that the suggested method provides determining the static formation temperatures with sufficient accuracy. As follows from these tables, in some cases the static formation temperatures estimated by two presented methods are very close.

The authors recommend the use of the proposed method when the temperature of the drilling fluid is not constant and stops in the mud circulation are documented. The authors will be glad to test this methodology at new results of thermal measurements in boreholes with the aim to obtain the reliable statistical data.

Conclusion

It is shown that the earlier proposed method for prediction of formation temperatures in permafrost regions from temperature logs in deep wells (Kutasov and Eppelbaum, 2003) can be applied to process results of bottom-hole temperature surveys in oil and gas exploration. Three field cases and one synthetic example are used to show the validity of this approach. The results of calculations are favourable compared with those obtained after the Generalized Horner Method (GHM). The authors hope to

Table 4. Results of determining the formation temperature after Formula (9). R is the squared averaged temperature deviation.

t_s (h)	T_s (°C)	T_s^* (°C)	ΔT (°C)	t_s (h)	T_s °C	T_s^* (°C)	ΔT (°C)
Andaverde et al. (2005), Hl31, T_f = 262.9 °C, t_c = 2.5 h, r_w = 0.106 m, a = 0.0036m^2/h, R = 4.3 °C				**Roax et al. (1980), T_f = 111.3 °C, t_c = 12.0 h, r_w = 0.100 m, a = 0.0027 m^2/h, R = 0.4 °C**			
6	183.6	179.8	3.8				
12	206.9	211.3	-4.4	14.3	83.9	83.7	0.2
18	219.0	225.1	-6.1	22.3	90.0	90.5	-0.5
24	231.9	233.0	-1.1	29.3	94.4	94.1	0.3
30	239.8	238.1	1.7				
36	247.7	241.7	6.0				
Andaverde et al. (2005), Hl30, T_f = 259.6 °C, t_c = 2.5 hr, r_w = 0.106 m, a = 0.0036m^2/h, R = 4.3 °C				**Cao et al. (1988), T_f = 122.5 °C, t_c = 5.0 hr, r_w = 0.108 m, a = 0.0054 m^2/h, R = 0.7 °C**			
6	178.6	172.5	6.1	2	91.7	90.7	1.0
2	198.9	205.5	-6.6	6	102.4	103.7	-1.3
8	211.4	220.0	-8.6	10	107.9	108.8	-0.9
4	225.8	228.2	-2.4	14	111.3	111.7	-0.4
30	235.1	233.6	1.5	18	113.6	113.5	0.1
36	240.4	237.3	3.1	22	115.2	114.8	0.4
42	247.1	240.1	7.0	30	117.1	116.5	0.6
				50	119.1	118.6	0.5

Table 5. Results of determining the formation temperature after Formulae (7) and (9). R is the squared averaged temperature deviation.

Case, Reference	Points	t_c (h)	t_s (h)	T_f ± R, °C	
				NM	GHM
HL31	6	2.5	6 - 36	269.4 ± 10.1	262.9 ± 4.3
HL30	7	2.5	6 - 42	266.2 ± 9.7	259.6 ± 4.3
Roax et al. (1980	3	12.0	14.3 0- 29.3	111.0	111.3 ± 0.3
Cao et al. (1988)	8	5.0	2 – 50	121.6 ± 0.6	122.5 ± 0.4

apply this method on a set of thermal borehole data measurements with the aim to obtain the reliable statistics.

ACKNOWLEDGEMENTS

We want to thank Dr. Edgar R. Santoyo Gutierrez for providing us with some data related to Wells HL31 and HL30. The authors would like to thank two anonymous reviewers, who thoroughly reviewed the manuscript, and their critical comments and valuable suggestions were very helpful in preparing this paper.

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