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A NEW METHOD FOR THE ANALYSIS OF STATIC FORMATION TEMPERATURE TESTS

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ABSTRACT

The static formation temperature test (SFTT) is a means of determining formation temperatures early in the drilling of a geothermal well. A knowledge of formation temperatures may be useful in deciding on the depth at which to set production casing. In addition an estimate of formation temperatures several months earlier than could be obtained by allowing the well to heat up after completion could be influential in deciding on drilling strategy.

A new technique for the analysis of SFTT data is presented. The technique has been found to be easy to use and at least as accurate as other techniques.

INTRODUCTION

The static formation temperature test (SFTT) is a method by which the undisturbed reservoir temperature can be estimated during drilling. The test is usually confined to fairly shallow depths, before significant circulation losses have been experienced.

The test is expensive to carry out, not in terms of the sophistication of the equipment used or the analysis, but because it is necessary to halt drilling for several hours and remove the drill-string from the wellbore. However, the advantage of the SFTT is that it offers the possibility of estimating reservoir temperatures perhaps two to three months before they can be estimated by well completion and heat-up, and this can be very valuable in terms of planning exploration and development programmes.

DEVELOPMENT OF THE METHOD

The equation which governs the temperature distribution surrounding the wellbore is the thermal diffusion equation. When written in radial co-ordinates it has the following form:

$$\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial T}{\partial R}\right) = \frac{\rho C_p}{k}\frac{\partial T}{\partial t} \qquad (1)$$

Implicit in the use of this equation are the following assumptions:

- radial symmetry exists with the wellbore as the axis.
- the formation is homogeneous and radially infinite, with constant properties.
- there is no vertical heat flow (vertical temperature gradients).
- heat flow is by conduction only.

Initially before the well is drilled all the rock surrounding the wellbore is at the formation temperature T_f. During circulation the temperature at the wellbore is held at T_o and a thermal front propagates a small distance out into the formation. However, a large distance from the wellbore the rock temperature is unchanged. When circulation ceases the temperature distribution which has been set up during circulation begins to decay back towards the original formation temperature. The boundary and initial conditions describing this situation are as follows:

The initial condition is:

$$T(R,0)=T_f \qquad (2)$$

The inner boundary condition throughout the circulation time is:

$$T(R_w,t)=T_o \qquad (3)$$

and after circulation is:

$$\frac{\partial T}{\partial R}_{R=R_w} = 0 \qquad (4)$$

Finally the outer boundary condition is:

$$T(\infty,t)=T_f \qquad (5)$$

Equation (1) and its boundary conditions (2) to (5) are non-dimensionalised as follows:

non-dimensional radius $r = R/R_w$

non-dimensional time $\tau = t/\eta$ where $\eta = \frac{C_p \rho R_w^2}{k}$

non-dimensional temperature $\theta = \frac{T_f - T}{T_f - T_o}$

to become $\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta}{\partial r}\right) = \frac{\partial \theta}{\partial \tau}$ (6)

with boundary conditions

$\theta(r,o)=0$

$\theta(\infty,\tau)=0$

and during circulation $\theta(1,\tau)=1$ and after circulation has ceased $\frac{\partial \theta}{\partial r}_{r=1} = 0$

Transforming the problem into the Laplace space, the resulting ordinary differential equation is solved in conjunction with the initial and outer boundary conditions. The solution is:

$$\bar{\theta}(r,s)=BK_o(r\sqrt{s}) \qquad (7)$$

where B is an unknown constant.

The Laplace transform in equation (7) can be inverted to give:

$$\theta(r,\tau) = \frac{B}{2\tau} e^{\frac{1}{-4\tau}} \qquad (8)$$

which may be rewritten in dimensional form at the well-bore as:

$$T(R_w,t)=T_f - \frac{\lambda\eta(T_f-T_o)}{t} e^{\frac{\eta}{-4t}} \qquad (9)$$

where $\eta=\frac{C_p \rho R_w^2}{k}$ and $\lambda=B/2$

It must be emphasised that the solution expressed by equation (9) is a general one which satisfies the governing equation (1) and the initial and outer boundary conditions only i.e. that initially and for large distances from the wellbore the temperature is always

As the inner boundary condition is canplicated and a function of the circulation time t_c it was decided not to satisfy it directly. Instead, the time t was written as a linear function of circulation time, t_c, and time since circulation has ceased, Δt.
That is $t = \Delta t + pt_c$ where p is a constant. Hence equation (9) becomes:

$$T(R_w,t)=T_f-\frac{\lambda n(T_f-T_o)}{\Delta t + pt_c}\, e^{-\frac{n}{4(\Delta t + pt_c)}} \qquad (10)$$

Field test data can be used to match equation (10) in order to determine the values of λ and p that produce the best fit. This has been done for data from the Philippines where it was found that $\lambda = 6.28$ and $p = 0.785$ gave the best results.

It has been found in practice that η is usually small compared to $\Delta t + pt_c$ and so equation (10) can be simplified to:

$$T(R_w,t)=T_f-\frac{m}{\Delta t + pt_c} \qquad (11)$$

where m is a constant $m = \lambda\eta(T_f-T_o)$

Therefore a plot of temperature versus $\frac{1}{\Delta t + pt_c}$ should produce a straight line of slope m and the intercept on the temperature axis is equal to the undisturbed formation temperature. From the slope m, the formation and circulation temperatures, it is possible to determine η, and hence the thermal diffusivity of the formation, should this be required.

The following data was obtained from an SFTT carried out by the Energy Development Corporation of the Philippines National Oil Company on Leyte, Philippines (Paete, 1981).

Circulation time $t_c = 15$ hours

Circulation temperature $T_o = 65^oC$

Time (hrs)	$\frac{1}{\Delta t+0.785t_c} \times 10^5$	Temperature ^oC
2.58	1.93	93
3.58	1.81	88
4.58	1.70	99
5.58	1.60	108
6.58	1.51	112
7.58	1.43	117
8.58	1.36	120
9.58	1.30	126
10.58	1.24	133
11.58	1,19	133
12.58	1.14	134
13.58	1.10	137
14.58	1.05	141
15.58	1.02	146

The plot of temperature versus $\frac{1}{\Delta t+0.785t_c}$ is presented in Figure 1. The value of the formation temperature obtained by extrapolating the line to the temperature axis is $T_f=208^oC$ and the slope of the line is $6.29\times10^6 s^oC$. Thio result compares favourably with a stable temperature of 208^oC measured after the well had been completed and allowed to heat up. As the well-bore radius R_w 0.108 m, and the slope of the line has been found along with the formation temperature

$$m = 6.29\times10^6 s^oC = 6.28\ (T_f-T_o)\eta \qquad \text{then}$$

$$\eta = \frac{c_p\rho}{k} = \frac{m}{6.28(T_f-T_o)R_w^{\ 2}} = \frac{6.29\times10^6}{6.28(208-65)\times(0.108)^2}$$

$$= 0.60\times10^6 sm^{-2}$$

Typical values of $\frac{c_p\rho}{k}$ have been found from experience to be of the order of 0.5×10^6 to $1.0\times10^6 sm^{-2}$ which is consistent with frequently assumed rock values in published geothermal heat storage estimates.

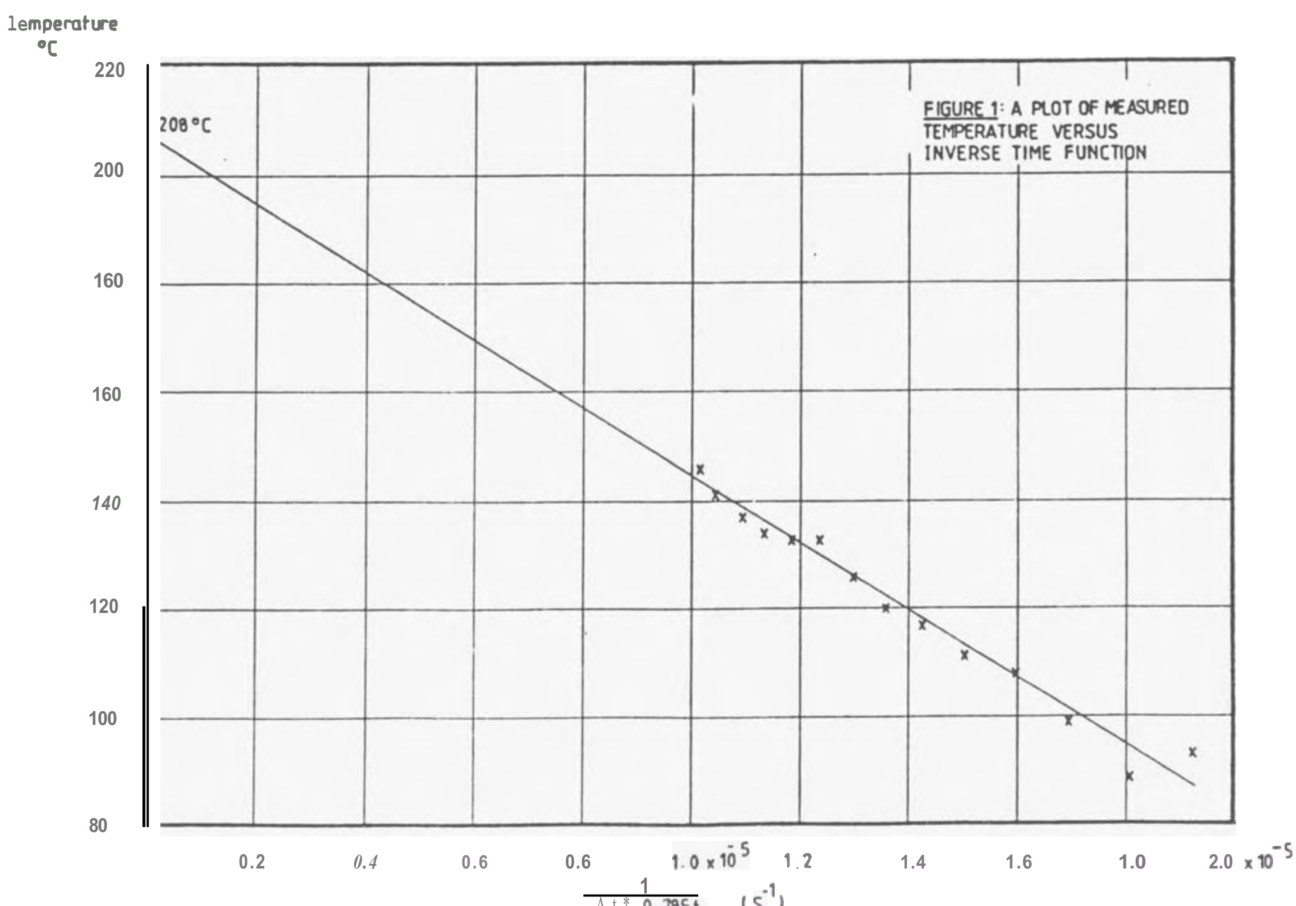

FIGURE 1: A PLOT OF MEASURED TEMPERATURE VERSUS INVERSE TIME FUNCTION

DISCUSSION

This type of analysis has been applied to SFTT data from a number of geothermal fields and the results have proved to be acceptable. It has several advantages over other techniques wnich make it ideal for field application.

This analysis avoids the use of correction terms such as those employed by Roux et al, (1979) and unique solutions are obtained explicity without the need for an iterative approach as in the method of Barelli & Palamà (1981).

The resulting error in the undisturbed formation temperature is typically $\pm$ 5°C, with a tendency to be on the lower side rather than the higher side of the measured formation temperature.

The thermal diffusivity $\frac{C_p \rho}{k}$ has typically been found to be in the vicinity of $0.5\text{-}1.0 \times 10^6 sm^{-2}$. This provides an inbuilt means of checking the reliability of a calculated undisturbed formation temperature found by using this type of analysis. Should the thermal diffusivity significantly deviate from this range then it is likely that the analysis is unrealiable.

It has been found that plots of early time data on the temperature versus inverse time function graph, lie above the straight line drawn in this analysis. With larger values of time the data points approach the line asymtotically. This is why this technique has a tendency to underestimate true undisturbed formation temperatures and is also the basis for stating that the value of the thermal diffusivity is a useful means of determining whether the test has proceeded long enough for the results to be reliable. Typically the duration of the test should be of the order of the circulation time.

It is a requirement of the SFTT test that heat transfer in the formation is by conduction only; there should be no significant permeability in the well before the SFTT is carried out. The thermal diffusivity estimate above provides a check on this also.

NOMENCLATURE

B a constant'

C_p specific heat capacity at constant pressure of rock in situ (J/kgK)

k conductivity of rock in situ (W/mK)

K_o modified Bessel function of the second kind of order zero

m slope of temperature versus $\frac{1}{\Delta t + pt_c}$ line (sK)

p a constant

r non-dimensional radius (R/R_w)

R Radius from axis of the wellbore (m)

R_w wellbore radius (m)

s Laplace transform variable

t time (s)

t_c circulation time (s)

Δt time since circulation stopped (s)

T temperature (°C)

T_f undisturbed formation temperazure (°C)

T_o circulation temperature (°C)

ρ density of rock in situ (kg/m^3)

λ a constant

non-dimensional temperature $\frac{T_f - T}{T_f - T_o}$

θ Laplace transform of non-dimensional temperature

non-dimensional time $\frac{kt}{C_p \rho R_w^2}$

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