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Initial Formation Temperatures by Inversion of Logged Temperatures in Geothermal Wells

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ABSTRACT

A method was implemented to compute the unknown initial condition for combined cycles of cooling (mud circulation) and heating (shut-in) heat transfer processes during drilling of geothermal wells with lost circulation effects. This initial condition is the unperturbed formation temperature of a geothermal reservoir. An objective function is constructed based on nonlinear least-squares and the difference between computed and measured temperatures during well shut-in as a function of time and position. The function is minimized subject to three independent variables. Well temperatures were computed from the corresponding direct problem with an assumed initial condition which is later modified using the Levenberg – Marquardt optimization algorithm (Marquardt, 1963). Solution of the heat transfer problem involves various physical of the well: the drilling pipe, the annular space and the surrounding formation. Implicit finite differences are used for the well regions and the 2-D conduction – convection formation problem is solved using the ADI scheme. Results of application are presented for one Mexican geothermal wells, which show reasonable matching of logged temperatures.

1. INTRODUCTION

Formation temperature is one of the most important parameters that need to be estimated for defining the feasibility of exploiting geothermal resources for electric power generation. Accurate estimation of formation temperatures may benefit a wide range of geothermal activities. These include the location of fluid inflow regions or lost circulation zones, estimation of heat reserves, evaluation of geothermal gradients, interpretation of electrical logs, evaluation of in-situ thermal conductivities, in-situ design of drilling fluids and cement slurries, well termination depth, among others (e.g., Grant et al., 1969; Ascencio et al., 1994; Garcia et al., 1998a, b; Santoyo et al., 2000; Espinosa-Paredes et al., 2001).

Formation temperatures are normally estimated from information obtained during drilling of a well, such as temperature logs. Methods to estimate formation temperature may be divided into dos classes. Class A or simple methods that concentrate on the bottom part of the well and are usually of a conductive nature. These methods are normally referred to in the geothermal industry as analytical or type curve methods. Many of the analytical methods have been developed from line-source theory, and the Horner method is probably the most representative and widely used of them. Limits of application and shortcomings of such method are discussed by Ascencio et al. (1994); Dowdle and Cobb (1975). Another simpler analytical method is the Spherical Radial Heat Flow Method (SRHFM) developed by Ascencio et al. (1994). This method appears to eliminate to a certain extent the problem of underprediction of the Horner method, it does not require explicitly the circulation time and may be useful to estimate formation temperatures in wells where the circulation time can not be determined.

Class B Methods attempt to reproduce the whole thermal history of both the drilling fluid column and surrounding formation (e.g., ; Garcia et al., 1998a, b, 2000; Raymond, 1969; Wooley, 1980, Beirute, 1991; Takahashi et al., 1997). These methods require a large amount of information about the well history such as the mud composition, inlet temperature, mud flow rate, circulation losses, well geometric characteristics and the thermophysical properties of mud, cement, pipe and surrounding rock. Some of this data is not well known yet or is completely unknown, thus limiting the usefulness of the simulation results. Lost circulation merely complicates simulation but its presence is useful in locating productive zones. Furthermore, if formation temperature can be obtained from simulation techniques based on mud temperatures, the formation temperature can be monitored during drilling (Takahashi et al., 1997) and the result would be a complete formation temperature profile.

2. FORMATION TEMPERATURES

2.1 Methodology

In the present study, the GEOTRANS computer code (Garcia et al., 2000) was used to simulate circulation and shut-in processes and to generate the temperature field in the well and the formation. Mud shut-in temperatures were then fitted to logged temperatures at different times and depths using the modified Levenberg - Marquardt optimization algorithm until an objective function was minimized. To carry out this process, the code was modified so that it could be called as a subroutine from a main program which performs the nonlinear least squares fitting of simulated to logged temperatures. The simulation starts from assumed values of initial formation temperature, porosity and circulation losses and their final values are obtained when the objective function is a minimum.

2.2 The GEOTRANS computer code

The GEOTRANS computer code (Garcia et al., 2000) allows estimation of temperatures in a well being drilled and the surrounding formation during circulation and shut-in (Garcia et al., 1998a) considering the effects of lost circulation into a porous medium (Luhesi, 1983) and assuming cylindrical geometry. Previous tests of the computer code without incorporation of the optimization algorithm are described in previous works (e.g., Garcia et al., 1998a, 2000). Wells from different Mexican geothermal fields have been analyzed using this code.

2.3 Minimization process outline

The inversion process used to estimate initial formation temperatures from logged and simulated mud shut-in temperatures is as follows.

2.3.1 Sequential process

1) Estimate or guess formation temperature, porosity and circulation losses at each depth.

2) Using these assumed parameters, use the GEOTRANS computer code to estimate mud temperatures during shut-in as a function of time.

3) Calculate the objective function to be minimized as:

$$FO(x_1, x_2, ...x_n) = \sum_{i=1}^{m} (T_{log,i} - T_{sim,i})^2 = f(T_f, \phi, W_{lc}) \qquad (1)$$

where $T_{log,,i}$ is the logged temperature and T_{sim} is the simulated temperature. The fitting or independent variables (x_1, x_2,……, x_n) are T_f or formation temperature, ϕ or formation porosity, and W_{lc} or fluid lost to the formation, and FO(x_1, x_2,…, x_n) is the fitting error or objective function to be minimized

4) Calculate updated formation temperatures and porosity and circulation losses at each zone.

5) Repeat the procedure from step 2 until satisfactory convergence.

Two input files were used for the inversion problem:

2.3.2 Well file

This file contains the geometric characteristics of the well, the thermopysical properties of drilling mud, cements, rocks, drilling pipe and casing pipe, mud flow rate into the well, mud inlet temperature, various parameters for controlling simulation of the circulation process and the type of initial formation temperature (linear, non-linear).

2.3.3 Initial conditions file

This file contains the various axial positions, the initially assumed formation temperature distribution, the distributions of porosity and circulation losses and various parameters for controlling the shut-in period. For convenience, the logged temperatures and their corresponding times are included in this file.

Fig. 1 shows a simplified flow diagram of the computational process.

The fitting variables of Equation (1) are formation temperature, porosity and circulation losses.; the first is related to the stabilized formation (initial) temperature, porosity is the channel through which the circulating mud flows out or the well and into the formation, and is related to the formation permeability at the well sandface.

2.4 Modeling of circulation losses

The process of lost circulation is illustrated in Fig. 2. Such losses are accounted for according to:

$$W_{lc} = \varphi . W_1 \qquad (2)$$

where W_{lc} is the flow rate of fluid lost to the formation, W_1 is the inlet fluid flow rate and φ is a multiplier that takes a value between 0 and 1. If $\varphi = 0$, no losses occur and if $\varphi = 1$, total lost circulation occurs. Knowing φ, the annulus mass balance can be performed and the axial velocity computed as well as the convective heat transfer in the rock.

2.5 Estimation of T_{sim} (Equation (1)

Estimation of the simulated temperature in the well is represented by the annulus temperature obtained from the following model. These temperatures are fitted to the to the experimental logged temperatures at different times and depths

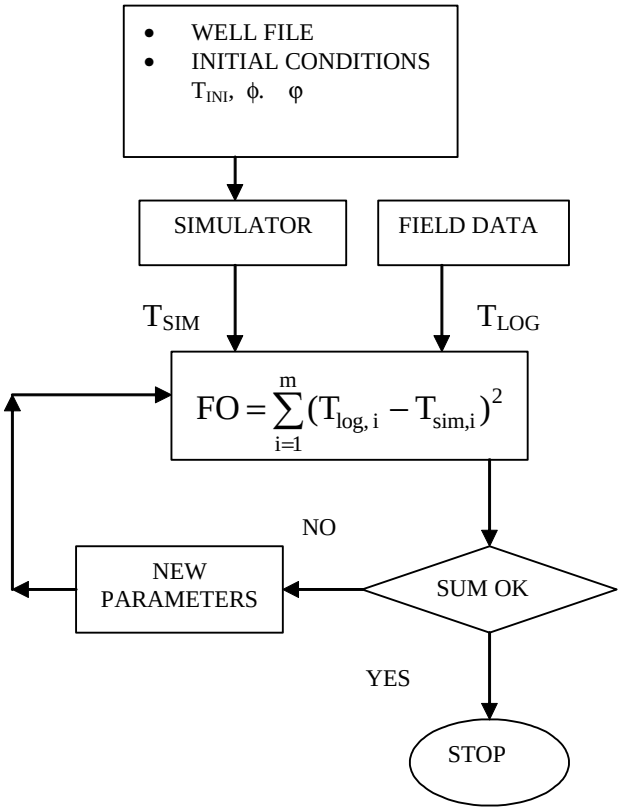

Figure 1. Schematics of the solution algorithm

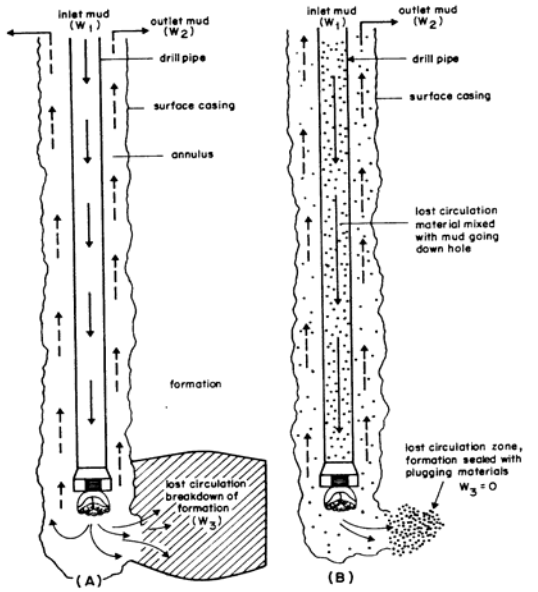

Figure 2. Physical model of lost circulation during drilling of a geothermal well.

Fig. 2 shows the physical model of drilling fluid circulation and lost circulation. Fluid enters the drill pipe at the top, exits at the bottom and flows up in the annulus. If lost circulation exists, some fluid flows into the formation and the amount of fluid exiting the well depends on the amount of circulation losses. The problem consists of a set of heat transfer partial differential equations describing the 2D transient temperature field T(z,r,t). Mass conservation considers incompressible flow in the axial and radial directions. The solution considers the heat transfer convective effects (boundary conditions). The well-formation interface is considered as a porous medium through which fluid may be lost or gained by the well. The mathematical formulation is generic and versatile since any vertical well can be studied and fluid loss or gain can be simulated at any point in the well. The model also considers the possibility of the drilling fluid being a mixture of air and mud or water. Use of the air fraction enables calculation of the effective mixture properties and porosity is used to estimate the formation effective properties. The heat transfer coefficients are corrected with the porosity. For shut-in conditions, it is assumed that heat conduction dominates.

2.5.1 Generic formulation

The fundamental assumptions of the model are:

(1) Axis-symmetric heat
(2) Isotropic rock formation with homogeneous porosity
(3) Formation, cement and pipe metal constant properties
(4) Negligible viscous dissipation effects
(5) No natural convection exists after shut-in

Assumption one considers symmetry of the well and formation about the well axis. This may no be quite true for a faulted formation. However it is used as a working hypothesis. Assumption two is necessary since the variation of formation thermal properties with depth and temperature is unknown for Mexican wells and work in that direction is underway. Homogeneous formation porosity is used in the radial direction, however it varies along the vertical direction (as inferred form lost circulation data), and is thus heterogeneous in that direction. In the present work, formation vertical porosity is found by trial an error and represents an average formation porosity.

The energy and continuity equations reduce to:

$$\rho C_p\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right)=k\left(\frac{1}{r}\frac{\partial T}{\partial t}+\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (3)$$

$$\frac{1}{r}\frac{\partial\left(r\,v_r\right)}{\partial r}+\frac{\partial v_z}{\partial z}=0 \quad (4)$$

where *r*,z are radial and axial coordinates, T is temperature, v is velocity, ρ is density, Cp is specific heat and k is thermal conductivity. The initial and boundary conditions are:

I. C.: $T(r, z, t=0) = f(r, z)$ (5)

BC1: $-k\left(\frac{\partial T}{\partial r}\right)_i = h\left(T_s - T_f\right)\ on\ A_i\ \ for\ all\ t$ (6)

BC2: $\left(\frac{\partial T}{\partial r}\right)_{r=0} = 0\ at\ r=0\ \ for\ all\ t$ (7)

B. C. 3: $v_z = W/\rho A_f\ \ at\ z=0\ \ for\ all\ t$ (8)

B. C. 4: $v_r = f\left(\phi, W, \rho, A_l\right)\ on\ A_i\ \ for\ all\ t$ (9)

where T_s is the solid temperature, T_f is the fluid temperature, A_i is the interfacial area between the rock formation and the fluid, W is the drilling fluid inlet mass flowrate, A_f is the cross sectional area for flow, ϕ is the formation porosity and A_l is the lateral flow area. Equations (3)-(9) define in generic form the problem posed.

In order to apply Equations (3)–(9), a simplified scheme of the physical well drilling system was considered to define all the regions of it. Fig. 3 shows schematically an axial region of length *1z*, the location and spacing of the radial mesh. The radii of this figure correspond to each one of the physical regions in which the well is divided. Five regions or components were identified as necessary in the heat transfer analysis: (1) the drill pipe; (2) the drill pipe wall; (3) the annular region; (4) the interface between the well wall (cement or rock formation) and the annular region for fluid return; and (5) the formation. On the basis of this configuration, a numerical method and a computer code were developed by consideration of a complete mathematical formulation of each of these regions.

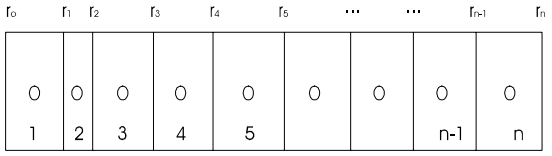

Figure 3. Radial node distribution. r indicates the boundaries of each radial region of the well and "o" indicates the cell where the computations are performed. The node height is Δz. Table 1 defines the regions.

Table 1. Regions defined by the nodes of Figure 2

Region name	Region number	Radial domain	Flow velocity [Eq. (2)]
Drill pipe	1	$r_0 \le r \le r_1$	$v_{z,1} \ne 0$
Drill pipe wall	2	$r_1 \le r \le r_2$	$v_{z,2} = 0$
Annulus	3	$r_2 \le r \le r_3$	$v_{z,3} \ne 0$
Interface between the well and annulus	4	$r = r_3$	$v_{z,4} = 0$
Formation	5	$r > r_3$	$v_{z,5} = 0$

2.5.2 Drill pipe (region 1)

This formulation calculates the temperature distribution in the drill pipe. Its model is complemented by the following three considerations:

- The inlet drilling fluid temperature (T_i) which is a boundary condition for the model.
- The mass flowrate of the drilling fluid (*W*) which is needed for calculating the fluid velocity (a boundary condition for the model; B.C.3).
- The temperature of the drill pipe metal wall (T_2) which is calculated by the drill pipe wall model (region 2).

Since the flow is in the axial direction, Equations (3)–(9) reduce to:

$$\rho_1 Cp_1\left(\frac{\partial T_1}{\partial t}+v_z\frac{\partial T_1}{\partial z}\right)=k_1\left(\frac{1}{r}\frac{\partial T_1}{\partial r}+\frac{\partial^2 T_1}{\partial r^2}+\frac{\partial^2 T_1}{\partial z^2}\right) \quad (10)$$

$$\frac{\partial v_{z1}}{\partial z}=0 \quad (11)$$

where the subscript 1 indicates the axial node where the temperature is calculated. The initial and boundary conditions are still valid except B.C.4 For convenience, the first boundary condition is rewritten as follows:

$$\text{B.C.1 } -k_1\left(\frac{\partial T}{\partial r}\right)_{r=r_1}=h_1(T_2-T_1) \text{ at } r=r_1 \quad (12)$$

As noted, the subscripts were changed to indicate the drill pipe region. The drilling fluid convective heat transfer coefficient h_1 is calculated by use of the appropriate correlations which are subsequently described.

2.5.3. Drill pipe wall (region 2)

This formulation calculates the temperature distribution in the drill pipe wall. The conditions here are defined by the following:

- the pipe wall temperature at the surface, T_{wa}, at $z = 0$
- the drilling fluid temperature (T_1) which is calculated by the drill pipe model (region 1)
- the temperature of the return fluid in the annulus (T_3) which is calculated by the annulus model (region 3)
- the drilling fluid mass flowrate in the drill pipe (W)
- the mass flowrate of drilling fluid in the annulus or its velocity.

At the boundary, the heat transfer coefficient, denoted by h_1, is needed and is calculated for the fluid in the drill pipe and the heat transfer coefficient for the fluid in the annulus h_2. In this case, Equations (3)–(9) reduce to:

$$\rho_2 Cp_2\frac{\partial T_2}{\partial t}=k_2\left(\frac{1}{r}\frac{\partial T_2}{\partial t}+\frac{\partial^2 T_2}{\partial r^2}+\frac{\partial^2 T_2}{\partial z^2}\right) \quad (13)$$

where the subscript 2 indicates that calculations are carried out for the drill pipe metal wall. The initial and boundary conditions I.C.1, B.C.1 and B.C.2 still apply but boundary conditions B.C.3 and B.C.4 are not needed. During the solution, B.C.1 is applied twice: at the interface denoted by $r = r_1$ and also at the interface $r = r_2$. Explicitly,

$$\text{B.C.1 } -k_1\left(\frac{\partial T}{\partial r}\right)_{r=r_1}=h_1(T_2-T_1) \text{ at } r=r_1 \quad (14)$$

$$\text{B.C.1.1 } -k_3\left(\frac{\partial T}{\partial r}\right)_{r=r_2}=h_2(T_2-T_3) \text{ at } r=r_2 \quad (15)$$

where the subscripts denote the particular region under consideration. If lost circulation is present, the velocity in the annulus is affected as well as the heat transfer coefficient h_2. These effects are properly considered in the present model.

2.5.4 Annular region (region 3)

This formulation estimates the temperature distribution of the annular region. The conditions for this region are

- the temperature at the bottom of the hole (T_1) which is calculated by the drill pipe model (region 1),
- the mass flow rate of drilling fluid (W),
- the temperature of the drill pipe metal wall (T_2) which is calculated by the drill pipe wall model (region 2), and
- the temperature of the annular fluid and the well inside wall (T_4) which is calculated by the interface model of the region 4.

The heat transfer coefficients at the drill pipe wall, $r = r_2$ denoted by h_2, and at $r= r_3$, denoted by h_3, are needed. For this case, Equations (3)–(9) simplify to

$$\rho_3 Cp_3\left(\frac{\partial T_3}{\partial t}+v_{z3}\frac{\partial T_3}{\partial z}\right)=k_3\frac{\partial^2 T_3}{\partial z^2} \quad \text{at } r_2\le r\le r_3 \quad (16)$$

$$\frac{1}{r}\frac{\partial(r v_r)}{\partial r}+\frac{\partial v_{z3}}{\partial z}=0 \quad \text{at } r>r_2 \quad (17)$$

$$\text{B.C.1.1 } -k_3\left(\frac{\partial T}{\partial r}\right)_{r=r_2}=h_2(T_2-T_3) \text{ at } r=r_2 \quad (18)$$

$$\text{B.C.1.2 } -k_3\left(\frac{\partial T}{\partial r}\right)_{r=r_3}=h_{ef}(T_4-T_3) \text{ at } r=r_3 \quad (19)$$

where the effective heat transfer coefficient h_{ef} considers the effect of porosity. In the present work this effect is quantified according to

$$h_{ef}=h_3(1-\phi) \quad (20)$$

where h_3 is the heat transfer coefficient for an impermeable wall and ϕ is the formation porosity.

2.5.5 Interface between the well wall (cement/rock formation) and annular region (region 4)

This formulation calculates the temperature distribution at the interface between the well wall (cement or rock formation) and the annular region for the fluid return. This interface is important since it mathematically couples the surrounding formation with the flow in the annulus and must guarantee continuity of heat flux during circulation and shut-in conditions. Its boundary conditions are:

- annulus fluid temperature (T_3) which is calculated by the annulus model (region 3),

- rock formation temperature with or without cemented sections (T_5) which is calculated by the formation model (region 5), and
- mass flowrate or velocity of the fluid ascending in the annulus (W).

The convective heat transfer coefficient needed in this case is h_3 which is related to the annular drilling fluid. In order to satisfy continuity of heat flow under circulation and shut-in conditions, the energy equation for this case is:

$$\text{B.C.1.4} \quad -k_3\left(\frac{\partial T}{\partial r}\right)_{r=r_3} + h_{ef}\,(T_4 - T_3) = k_{ef}\left(\frac{\partial T}{\partial r}\right)_{r=r_3} \qquad (21)$$

where k_{ef} is the effective thermal conductivity which depends on porosity and the thermal conductivities of the formation and the drilling fluid. This boundary condition guarantees continuity of heat flow under shut-in condition since for such conditions h_{ef} is zero, otherwise it is given by Equation (20).

2.5.6 Surrounding rock formation (region 5)

This module calculates the axial and radial temperature distributions in the formation with or without a cemented section. The conditions for this region are

- ambient temperature (Ta) at z D 0 for all r,
- temperature at the interface of the well wall (T_4) which is calculated by the heat transfer model of region 4
- the initial temperature which represents a boundary condition at $r \rightarrow \infty$. This temperature is the static or undisturbed formation temperature.

For this case, Equations (3)–(9) simplify to:

$$(\rho Cp)_{ef}\left(\frac{\partial T_f}{\partial t} + v_r\frac{\partial T_f}{\partial r}\right) = k_f\left(\frac{1}{r}\frac{\partial T_f}{\partial r} + \frac{\partial^2 T_f}{\partial r^2} + \frac{\partial^2 T_f}{\partial z^2}\right) \qquad (22)$$

$$\frac{1}{r}\frac{\partial (r\,v_r)}{\partial r} = 0 \qquad (23)$$

where the physical properties are given by:

$$(\rho C_p)_{ef} = (\rho C_p)_f\,(1-\phi) + (\rho C_p)_3\,\phi \qquad (24)$$

$$k_{ef} = k_3^{\phi}\,k_f^{(1-\phi)} \qquad (25)$$

where subscripts f and 3 correspond to the formation and the fluid flowing into the formation from the annulus, respectively. The convective term of Equation (22) implies the fluid lost to the formation moves radially and thus velocity depends on the formation porosity. The convective hest transfer coefficients and the details of this model are described in Garcia et al. (1998b).

Model solution is obtained by finite differences whereby the PDE´s described above are transformed into discrete equations using finite differences in an implicit form. The resulting non-linear algebraic equations are then solved iteratively. To start the solution, vertical distributions of initial formation temperature, porosity and drilling fluid losses are assumed. Then, the model given by equations (1) and (3) through (25) are solved and the annulus temperature is assigned to T_{sim}, and the objective function, Equation (2), is solved using the Levenberg- Marquardt optimization algorithm. If the sum of squares is not a minimum, the algorithm proposes new values of the fitting variables (formation temperature, porosity and drilling fluid losses) and the mathematical model is solved again to perform a new evaluation of Equation (2), an so on until the sum of the squared differences is a minimum. Figure 3 shows the flow diagram for the minimization process.

3. ILLUSTRATIVE RESULTS

Figure 4 shows a typical result of a simulation. In the figure, logged temperature profiles are shown as well as the corresponding simulated temperatures resulting from the optimization process. Also shown is the assumed temperature distribution as function of depth and the formation temperature profile resulting obtained from the simulation and optimization process.

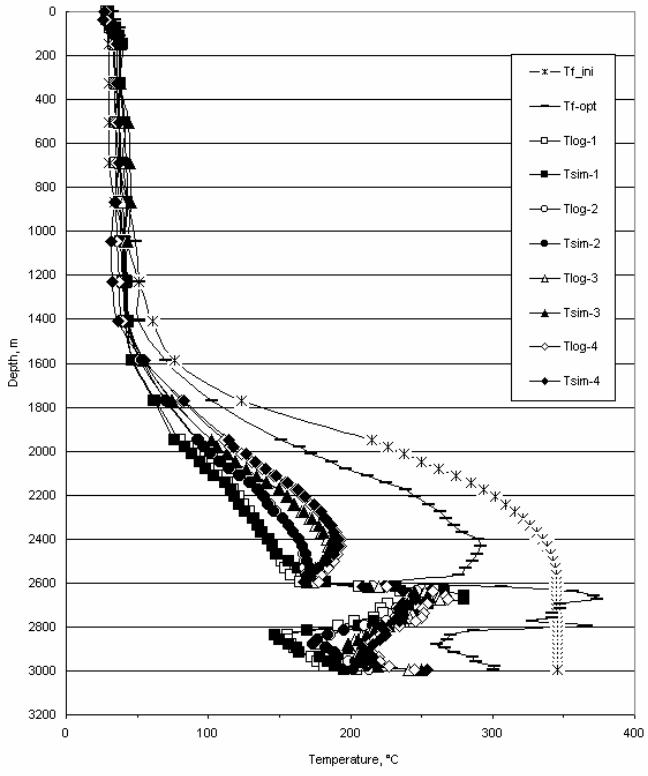

Figure 4 Logged and simulated temperatures for the test- well. The initially-assumed and the resulting formation temperatures are also shown.

For this well the initial formation temperatures were assumed based on information from nearby wells such that a kind of typical profile was assumed as the initial condition

for the simulation process. The well was cased to 2600 m, and the well total depth was 3100 m. Circulation losses were high in this well, and temperatures were logged from 1950 m to 3000 m only, such that "logged" temperatures had to be assumed from 0 to 1900 m.

It is observed that simulated and logged temperatures match well in the whole depth range and the trends exhibited by the logged temperatures are closely followed by simulated temperatures. The optimized formation temperatures follow well the initially assumed temperatures and at 2600 m, all logged temperatures joint at a single point causing a sudden decrease of the optimized formation temperature. This then grows rapidly and remains high (above 350°C) between 2600 and 2800 m, and finally decreases below 300°C between 2800 and 3000 m.

4. CONCLUSIONS

The GEOTRANS thermal simulator was modified to determine the reservoir initial temperature or initial formation temperature distribution considering lost circulation effects. The input data required are the logged temperatures and inlet flow conditions, besides the well geometric parameters and the thermopysical properties of its construction materials. However, to start the nonlinear least-squares optimization algorithm, an initial temperature distribution is required as well as the circulation losses. With these fitting parameters, the formation temperature can be reasonably estimated.

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