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COMPARATIVE STUDY OF THERMAL BEHAVIOR DURING DRILLING OF GEOTHERMAL WELLS USING MUD AND AIR-WATER AS DRILLING FLUIDS

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ABSTRACT

This work presents a comparative study of the thermal behaviour of drilling fluids and surrounding rock when air-water and conventional muds are used as drilling fluids. The computations were carried out with two numerical simulators: TEMLOPIV.2, which is used to compute the transient temperature disturbance when mud is employed, and GEOMIST when air-water mixtures are used as drilling fluid. In this analysis, data from well LV-4 from the Las Tres Vírgenes Mexican geothermal field are used. The results of simulation were compared with temperatures logged during the drilling process and a good approximation of computed results and field data was obtained. The results also show that the thermal disturbance due to circulation of an air-water mixture has a smaller thermal effect on the surrounding rock than the muds. For this reason, wells drilled with air-water mixture return faster to the undisturbed thermal state.

1. INTRODUCTION

One of the most important parameters during drilling and completion of geothermal wells is the temperature field. This parameter plays an important role in the design of slurries for well cementing, estimation of energy reserves, study of geothermal gradients, etc. At present, there exists several methods to determine the temperatures in wells during drilling. The most common are the empirical correlation's developed by API (1990) and Farris (1941). However, the correlations have had limited success in predicting downhole circulating temperatures in geothermal wells (Kutasov and Targhi, 1987). This is because such temperatures are usually overestimated since the correlations were originally developed for the oil drilling industry.

Also, static temperatures are obtained from temperature logs in combination with several classical analytical methods developed to infer static formation temperatures (SFT). However, the SFT values obtained in this way are always less than the initial temperatures of the formation (Nielsen et al., 1990; Santoyo et al., 1999). Finally, numerical simulators represent an important alternative for predicting the transient behavior of the temperature distribution in and around geothermal wells under drilling and completion conditions.

In the past, a number of computer programs have been developed to provide an approach to the solution of the heat transfer problem relating drilling fluid circulation, wellbore geometry and the surrounding formation. Some of these computer programs have used a pseudo-steady heat flow model in the wellbore with transient heat conduction in the formation (Raymond, 1969; Holmes and Swift, 1970; Arnold, 1990; García et al., 1998a). Many other computer programs have been developed which consider transient heat flow models in the wellbore with transient heat conductive model for the formation (Raymond, 1969; Keller et al., 1973; Wooley, 1980; Marshall and Bentsen, 1982; Corre et al., 1984; Beirute, 1991; Espinosa et al., 1994; Espinosa et al., 1999). Lost circulation phenomena are studied by García et al., (1998b).

On other hand, muds (water-oil based) have traditionally been used as drilling fluids. They serve to remove the drill cuttings, to cool and lubricate the bit, to cool the well interface for cementing the well casing, etc. However, air-water mixtures have been used more recently as drilling fluids. This allows elimination of some mud additives that potentially may pollute the surrounding environment and superficial water sources. Also, the drilling penetration is faster than with muds and some costs associated with lost circulation are reduced.

This work presents a comparative study of the thermal behavior of drilling fluids and surrounding rock when air-water mixtures and conventional muds are used as drilling fluids. The computations were carried out with two numerical simulators: TEMLOPI/V.2 (Espinosa et al., 1999), which is used to compute the transient temperature disturbance when mud is employed, and GEOMIST (García et al., 1999) which is used when air-water mixtures are employed as drilling fluids.

TEMLOPI/V.2 is a computer program based on a mathematical model which considers two-dimensional and fully transient heat transfer during drilling and shut-in conditions in and around a geothermal well (Espinosa et al., 1999). GEOMIST employs an extended homogeneous flow model (EHFM) to estimate the effects of multiphase flow due to air, drill cuttings and mist (air-water). Forced convection is considered during circulation of fluids, when the drilling operation is going on, while natural convection is included when stop periods take place (García et al., 1999).

Results are compared with data from well LV-4 from the Las Tres Vírgenes Mexican geothermal field.

2. PHYSICAL MODEL

The physical model of drilling fluid circulation on which the TEMLOPI/V.2 and GEOMIST computer programs are based is given by García et al. (1998b) and is shown schematically in Fig. 1. The fluid temperature in the wellbore depends upon a number of different thermal processes as can be seen in Fig. 1. In region 1, the fluid enters the drill pipe at a specified temperature. As the fluid passes down the pipe in the z direction, its temperature (T_1) is determined by the rate of heat convection down the drilling pipe and heat exchange with the annulus fluid. In region 2, the drill pipe wall temperature (T_2) is determined by the rate of heat convection between the wall and flow down the drill pipe and up in the annulus. In region, 3 the circulation process requires that the fluid temperature at the exit of the drill pipe be the same as the fluid temperature at the entrance of the annulus. In this region, the temperature (T_3) is determined by the rate of heat convection up the annulus, the rate of heat exchange between the annulus and the drill pipe, and the rate of heat exchange between the formation adjacent to the annulus (T_4) and the fluid annulus. After the flow is stopped, the TEMLOPI/V.2 computer program (Espinosa et al., 1999) considers an axis-symmetric heat conduction situation while the GEOMIST computer programs considers natural convection (García et al., 1999).

3. MATHEMATICAL MODELS OF THE TEMLOPI/V.2 AND GEOMIST COMPUTER PROGRAMS

The TEMLOPI/V.2 formulation is based on the following fundamental assumptions:

- Cylindrical geometry
- Single-phase flow
- The rock formation is isotropic and impermeable.
- The physical properties of the formation, cement and pipe metal are constant (thermal conductivity, density, heat capacity and viscosity).
- Flow is fully developed and incompressible, circulates at a constant rate, and its physical properties are constant.
- Heat transfer in the drilling pipe fluid and annulus is by axial convection and by axial and radial conduction.
- Heat transfer in the pipe wall and formation is by axial and radial conduction.
- Viscous dissipation and thermal expansion effects are neglected.

The GEOMIST formulation is similar to that of TEMLOPI/V.2, however it includes the following additional assumptions:

- The two-phase flow of air and water is homogeneous.
- Air is considered as an ideal gas.

3.1 Mathematical formulation of TEMLOPI/V.2

The energy balances governing the system are described by four partial differential equations, which are written in generic form as:

$$r_i C_{p,i}\left(\frac{\partial T_i}{\partial t} + v_{z,i}\frac{\partial T_i}{\partial z}\right) = \frac{k_i}{r}\frac{\partial T_i}{\partial r} + k_i\frac{\partial^2 T_i}{\partial r^2} + k_i\frac{\partial^2 T_i}{\partial z^2} \qquad (1)$$

where subscript i (=1,2,..,5) indicates the axial node where the temperature is calculated, z and r are the cylindrical co-ordinates in the radial and axial directions, T is the temperature, v is the flow velocity, ρ is the density, C_p is the specific heat and k is the thermal conductivity. In Table 1 are shown the conditions and regions of application of equation (1).

The continuity equations for incompressible flow in regions 1 and 3 is given by

$$\frac{\partial v_{z,j}}{\partial z} = 0 \qquad j = 1,3 \qquad (2)$$

The initial and boundary conditions for equations (1) and (2) are:

I.C. $\quad T(r,z,t=0) = f(r,z) \qquad (3)$

B.C.1 $\quad q = -k\left(\frac{\partial T}{\partial r}\right)_{int} = h(T_s - T_m) \quad$ on A_{int}, (4)

B.C.2 $\quad \left(\frac{\partial T}{\partial r}\right)_{r=0} = 0 \quad$ at $r = 0$, (5)

B.C.3 $\quad v_{z,1} = \frac{W}{rA_d} \quad$ at $z = 0$, (6)

where T_s is the solid temperature, T_m is the drilling fluid temperature, A_{int} is the interfacial area between the rock formation and the fluid, W is the drilling fluid mass flowrate, A_d is the drill pipe cross-sectional area for flow and h is the heat transfer coefficient. The inlet drilling fluid temperature (T_{in}) is also a boundary.

Equations (1)-(6) defines in generic form the problem with boundary and initial conditions to be solved.

- Drill pipe (Region 1)
For this region, equation (1) is applied with $i = 1$. The initial and boundary conditions are still valid.

-Drill pipe metal wall (Region 2)
For this region, equation (1) is applied with $i = 2$. The initial and boundary conditions are still valid except B.C.3. The other boundary conditions needed is:

B.C.4 $\quad -k_3\left(\frac{\partial T_3}{\partial r}\right)_{r=r_2} = h_2(T_2 - T_3) \quad$ at $r = r_2 \qquad (7)$

where h_2 is the heat transfer coefficient for the fluid in the annulus. The metal pipe wall temperature at the surface T_{wa} is also a boundary condition for the model.

- Annular region (Region 3)
For this region, equation (1) with $i = 3$ and equation (2) are applied. The initial and boundary conditions given by equations (3) and (7) still apply. The additional boundary conditions are:

B.C.5 $\quad -k_3\left(\frac{\partial T_3}{\partial r}\right)_{r=r_3} = h_3(T_4 - T_3) \quad$ at $r = r_3 \qquad (8)$

B.C.6 $\quad v_{z,3} = \frac{W}{r_3 A_a} \quad$ at $z = z_{max} \qquad (9)$

where A_a is the annulus cross-section area and z_{max} is the bottom of the wellbore. Other conditions needed for the solution of the model are the temperature at the bottom of the hole (T_1, at $z = z_{max}$), the temperature of the drill pipe wall (T_2) and the temperature of the well inside wall or sand face (T_4).

- Interface between the well wall and the annular region for fluid return (Region 4)
The boundary conditions are the annulus fluid temperature (T_3) and the rock formation temperature (T_5). Heat flow continuity under circulation and shut-in conditions requires satisfaction of the energy balance given by

B.C.7 $-k_3\left(\frac{\partial T_3}{\partial r}\right)_{r=r_3} + h_3(T_4 - T_3) = k_5\left(\frac{\partial T_5}{\partial r}\right)_{r=r_3} \qquad (10)$

This boundary condition guarantees continuity of heat flow under shut-in condition since for such conditions h_3 in considered zero, otherwise it is given by B.C.5.

- Formation (Region 5)

For this region equation (1) is applied with $i = 5$. The boundary conditions for this region are: ambient temperature (T_a) at $z = 0$ for all r, temperature at the interface of the well wall (T_4), and the initial temperature given by equation (3) which represents a boundary condition at $r \rightarrow \infty$. This temperature is the static or undisturbed formation temperature.

The heat transfer coefficient for laminar flow in the annulus is calculated using the Seider and Tate (1936) correlation. For laminar flow inside the drill pipe, its analytical solution is employed. For transitional and turbulent flow, Gnielinsky's (1976) correlation is applied.

3.2 Mathematical formulation of GEOMIST

The mathematical model of the GEOMIST computer program is based on the balance equations of mass, momentum and energy, a state equation. Three regions are considers in GEOMIST: (i) drill pipe, (ii) annulus and (iii) formation. Heat flow from one region to another is modelling as a thermal resistance in the wellbore.

(i) Drill pipe formulation

$$\left[(rC_pA)_1 + (rC_pA)_{ac}\right]\frac{\partial T_1}{\partial t} = \dot{V}r\left(\frac{\partial j}{\partial z} + \frac{1}{r}\frac{\partial x}{\partial z}\right) + \dot{V}\left[(rC_p)_1\frac{\partial T_1}{\partial z} + \frac{1}{r}(1 - T'b)\frac{\partial p}{\partial t}\right] + 2pU_{12}(T_2 - T_1) \quad (11)$$

$$\frac{\partial}{\partial z}(rv^2) + \frac{\partial p}{\partial z} + F + W = 0 \quad (12)$$

$$\frac{\partial}{\partial z}(rv) = 0 \quad (13)$$

$$p = rRT \quad (14)$$

where $\dot{V}$ is the volumetric flow rate, j and x are the kinetic and potential energy, respectively, p is the pressure, U_{12} is the overall heat transfer coefficient between the drill pipe and annulus, and T_1 and T_2 are the temperatures of the fluid in the drill pipe and the annulus, respectively. The terms F and W of equation (12) represent friction and gravity effects, respectively.

The initial condition is given by equation (3) whereas the boundary conditions are defined at the inlet of the drill pipe, $z = 0$.

(ii) Annulus

In this region, three-phase flow is present due to the fact that the drill cuttings represent the solid phase and air and water represent the other phases. The balance equations in this region are given by:

$$\left[(rC_pA)_2 + (rC_pA)_{ac}\right]\frac{\partial T_2}{\partial t} = \dot{V}r\left(\frac{\partial j}{\partial z} + \frac{1}{r}\frac{\partial x}{\partial z}\right) + \dot{V}\left[(rC_p)_2\frac{\partial T_2}{\partial z} + \frac{1}{r}(1 - T'b)\frac{\partial p}{\partial t}\right] + 2pU_{23}(T_3 - T_2) - 2pU_{12}(T_2 - T_1) \quad (15)$$

$$\frac{\partial}{\partial z}(e_a r_a v_a^2) + \frac{\partial}{\partial z}(e_s r_s v_s^2) + \frac{\partial p}{\partial z} + F + W = 0 \quad (16)$$

where subscripts a and s designate the gas (air) and solid (drill cuttings) phases respectively, U_{23} is the overall heat transfer coefficient between the annulus and the rock formation and e is the gas phase volume fraction. In this case, subscript 2 indicates that the calculations are carried out for the annular region.

The balance equations for the drill cuttings are given by

$$\frac{\partial}{\partial z}(e_s r_s v_s) = 0 \quad (17)$$

$$\frac{\partial}{\partial z}(e_s r_s v_s^2) + W_s - \Xi = 0 \quad (18)$$

where W_s and Ξ are the buoyancy and aerodynamic forces, respectively.

(iii) Formation

For this region, GEOMIST applies the same mathematical model that TEMLOPI/V.2 uses to compute the axial and radial transient temperature distribution of the rock formation.

4. NUMERICAL SOLUTIONS

In the numerical solution of TEMLOPI/V.2 and GEOMIST, the geothermal well and the surrounding formation are represented by a two-dimensional mesh-centred grid consisting of a variable number of radial and vertical elements. The governing equations can be written for each element of the grid. The differential equations described above are transformed into discrete equations using the technique of finite differences in an implicit form. The implicit scheme results in a set of non-linear equations and are solved iteratively. In the formation, heat transfer is two-dimensional and the solution is obtained using the alternating direction (ADI) algorithm.

5. RESULTS AND DISCUSSION

This comparative study was applied to the LV4 Mexican geothermal well. This is located in the Las Tres Vírgenes geothermal field. It is 2500 m deep and was completed in June 1996 after 150 days since the start of drilling. The geometric characteristics of the well are as follows. Hole diameters are 26", 17-½", 12-¼", and 8-½"; Casing diameters are 20", 13-3/8" and 9- 5/8". The liner has a diameter of 7" and runs from 1339 m to 2492 m. During the construction of this well, several temperature logs were run and only the logs run during the fourth stage (T-9, T-10, T-11 and T-12) were used in the present study because an air/water mixture (a mist) was used in this stage of the drilling process.

Fig. 2 shows the thermal behaviour of well LV4 after 5 days of circulating. Mud and mist were used as drilling fluids for comparison purposes. Simulations were carried out using both, the TEMLOPIV.2 and GEOMIST simulators. It can be seen that when mud is used as drilling fluid, an important decrease in the well temperatures occurs. This is mainly due to the thermal properties of the mud to carry energy from the well to the surface. However, when mist is used as drilling fluid, the well temperature shows a small decreasing change, and thus well cooling for cementing purposes is not as efficient. For this reason, the use of mists in the drilling process is used only in the final drilling stage or when circulation losses exist.

Figs. 3 through 6 show the well thermal recovery process after 6, 12, 18 and 24 hours of stopping fluid circulation (shut-in). Also plotted in these figures are the geothermal temperature profile and temperature log T-9 for comparison purposes. A quantitative analysis indicates that the temperatures predicted with GEOMIST have good agreement with the logged temperatures. In all instances, the deviation between the predicted and the actual measured temperatures range from 0.1 ºC to 3.5 ºC for the shut-in profiles between 0 and 24 hours since circulation stopped. However, temperatures predicted with TEMLOPIV.2 were very different due to the properties of the drilling fluid (mud) employed for the simulation. These results are expected since temperatures were logged when drilling with mist, however, the comparison is useful to understand the differences in the thermal processes that these two drilling fluids give rise to and to choose the best option during the construction of geothermal wells.

Fig. 7 shows the initial and simulated temperature profiles of the surrounding rock at three different depths for the two cases describe above. It is observed that the initial temperature was very little disturbed when mist was used as drilling fluid. The major change occurred at the bottom of the well and the disturbance amounted to some 8 to 10 ºC, approximately. Nevertheless, when mud was used, the major disturbance was between 140 ºC and 150 ºC at the bottom of the hole. For this reason, the well will return faster to the undisturbed (initial) temperature when drilled using a mist than when drilled using mud.

6. CONCLUSIONS

A comparative study was performed to understand the thermal behaviour of geothermal wells drilled using mists (air/water mixtures) or mud as drilling fluids and to predict the cooling of the surrounding rock during the drilling process. The GEOMIST and TEMLOPIV.2 thermal transient simulators were used for this purpose. The analysis was developed using data from well LV-4 from the Las Tres Virgenes Mexican geothermal field. The results show significant cooling effects of the surrounding rock when mud circulates during the construction process. However, when mist was used the surrounding rock temperature changes very little but matches well the temperature logs taken during the drilling of the well with mist, as expected.

7. REFERENCES

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Table 1. Range of application of equation (1)

Region	i [Eq. (1)]	Range (Fig. 1)	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	$r > r_3$	$v_{z,5} = 0$

* Boundary condition

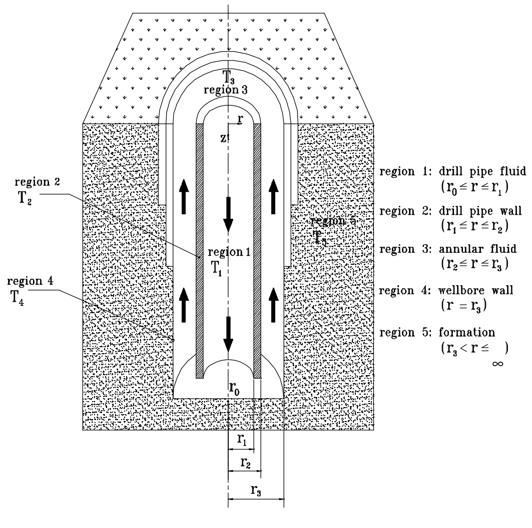

Fig. 1. Physical model of fluid circulation in geothermal wells during drilling. The five heat flow regions described by TEMLOPI/V.2 are also shown**.**

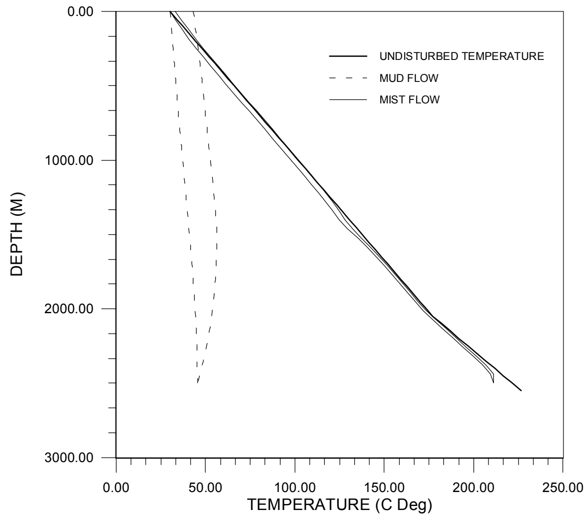

Fig. 2. Drill pipe and annulus temperatures in well LV-4 after 5 hours of circulation.

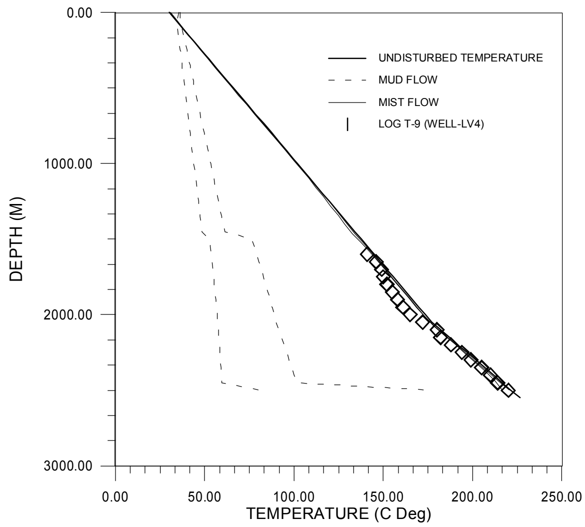

Fig. 3. Drill pipe and annulus temperatures in well LV-4 at 6 hours shut-in time**.**

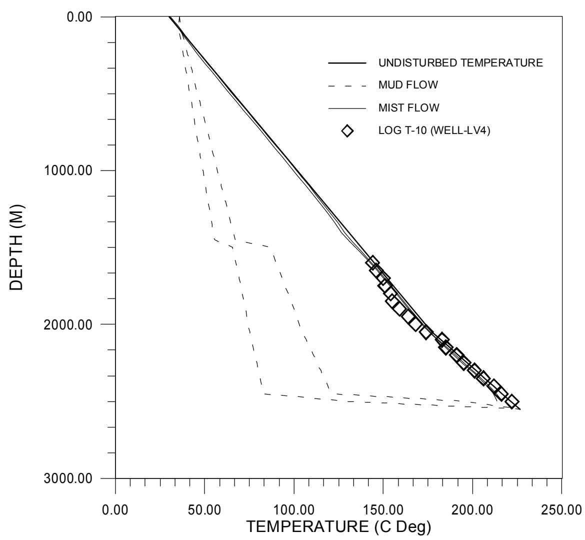

Fig. 4. Drill pipe and annulus temperatures in well LV-4 at 12 hours shut-in time.

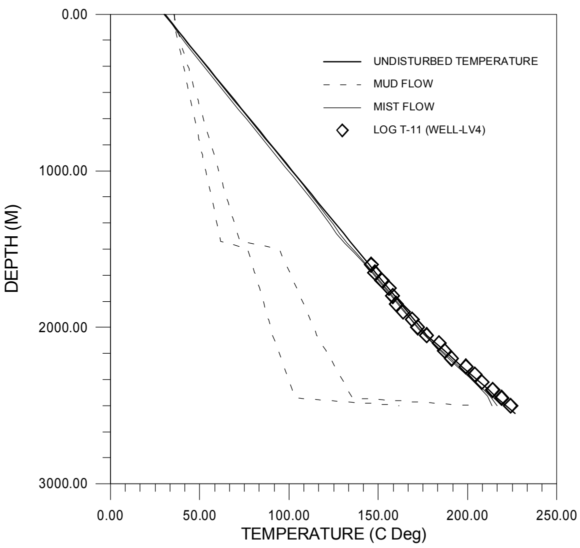

Fig. 5. Drill pipe and annulus temperatures in well LV-4 at 24 hours shut-in time.

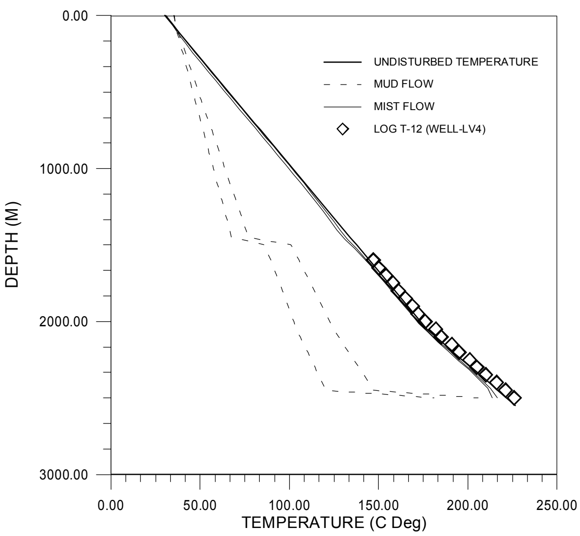

Fig. 6. Drill pipe and annulus temperatures in well LV-4 at 6 hours shut-in time

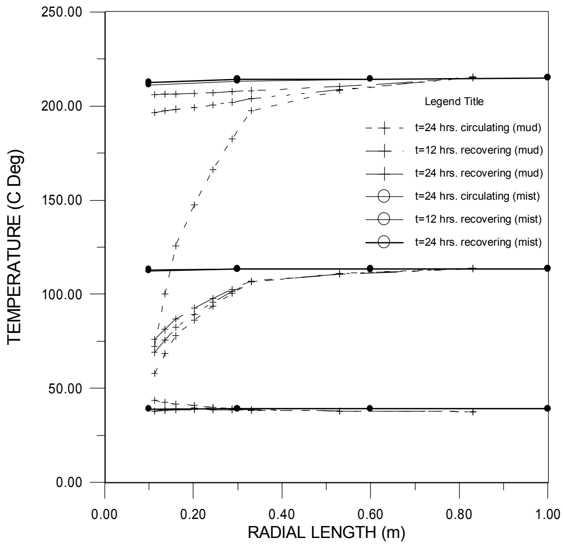

Fig. 7. Temperature of the rock surrounding well LV-4 circulation and shut-in.