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A Model of Heat Transfer in Geothermal Wells with Lost Circulation

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ABSTRACT

This paper describes a model of heat transfer in geothermal wells with lost circulation. The governing equations of heat transfer in a geothermal well drilling with lost circulation are solved. The transport processes modeled include flow of fluid in the drilling pipe and annulus, heat transfer in the drilling pipe wall and conductive and convective heat flow in the formation. Solution allows estimation of temperatures in and around a well as function of time and vertical and radial position. The model is closed using heat transfer and fluid friction correlations. Physical properties of drilling fluids (muds and water/air mixtures), cements, rocks and pipes, implemented via numerical routines or as databases complement the model. Numerical solution follows implicit finite differences and the Thomas algorithm is used for their solution Heat transfer in the formation is 2D and is solved via an ADI scheme. A unique feature of the model is that it simulates drilling fluid losses at any position along the uncased wellbore and its effect is accounted for as thermal convection in the formation. The simulated temperatures as function of depth and time for the circulation and shut-in periods are then analyzed. Previous code validation was performed by comparison against data from the literature and analytical solutions. Results of application to the well H-26 from Los Humeros geothermal field are presented. The shut-in logged temperatures were reproduced in the presence of lost circulation, and the formation temperatures are obtained by trial and error.

1. Introduction

Loss of drilling fluid to surrounding formations is normally encountered during drilling of geothermal wells, and these losses provide a good indication about productive horizons in geothermal reservoirs. However, from the point of view of well drilling, lost circulation normally increases the time and cost for well completion and may be considered as an unwanted phenomenon. Yet, the information obtained during well drilling may be analyzed to extract valuable information about the geothermal reservoir such as formation temperatures and formation porosity or permeability. Drilling fluid losses are associated with permeable horizons in the reservoir. Temperature logs are used to obtain unperturbed formation temperatures and for the analysis of thermal gradients and temperature inversions and their relation to the presence of production zones. Also, temperature logs are helpful in locating places where heat is lost to the formation (Grant et al., 1982; Garcia et al., 1998a,b) by simulating the transient heat transfer processes in the well.

Methods to estimate unperturbed formation temperatures focus on the bottom part of the well where temperatures are measured. Accurate knowledge of such temperatures is one of the problems that the geothermal industry needs to solve. Such methods are normally referred to as analytical methods (e.g., Takahashi et al., 1997; Santoyo et al., 1999). For a series of drilling stages in a well, estimation of unperturbed temperatures is called stage testing (Grant et al., 1982). A review of such methods is given in detail elsewhere (e.g., Ascencio et al., 1994; Garcia et al., 1998b; Santoyo et al., 1999). Examples of these are the Horner (Dowdle and Cobb, 1975), the improved Horner (Roux et al., 1979), the Two-point (Kritikos and Kutasov, 1988), the Spherical (Ascencio et al., 1994) and the Hasan and Kabir, (1994) methods. The present code has been used for estimating formation temperatures and formation porosity

Numerical simulation of the whole thermal history of the drilling fluid column and the surrounding formation has been studied. The simulators employed include models ranging from pseudo-steady (Raymond, 1969; Garcia et al., 1998a) to fully transient, with constant or variable properties (Mondy and Duda, 1984; Beirute, 1991), and drilling fluid losses (Takahashi et al., 1997; Garcia et al., 1998b). These tools require an extensive amount of information about the well drilling history such as the fluid composition, inlet and outlet mud temperatures, fluid circulation rate, well geometric characteristics and the thermophysical properties of drilling fluids, cements, casings, pipes and surrounding rocks. Studies that account for drilling fluid losses are scarce. Luhesi (1983) proposed a formation/fluid model based on a simplified radial heat transfer equation that includes radial fluid motion and heat flow to the surrounding rock. Luhesi's model is applicable to the bottom 10-20 m of the borehole. Takahashi et al., (1997) modeled fluid losses as a mass and energy source in the reservoir. Fluid motion is assumed to follow Darcy's law. This model considers the drilling fluid inlet and outlet temperatures to obtain the fluid and formation temperatures. A model for estimating the transient temperature field in and around a geothermal well during fluid circulation and shut-in was developed by Garcia et al. (1998b) that is applicable to the uncased part of the well. In the present work, the heat transfer model is described and the results are presented for well H-26.

2. Mathematical Model

Fig. 1 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 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.

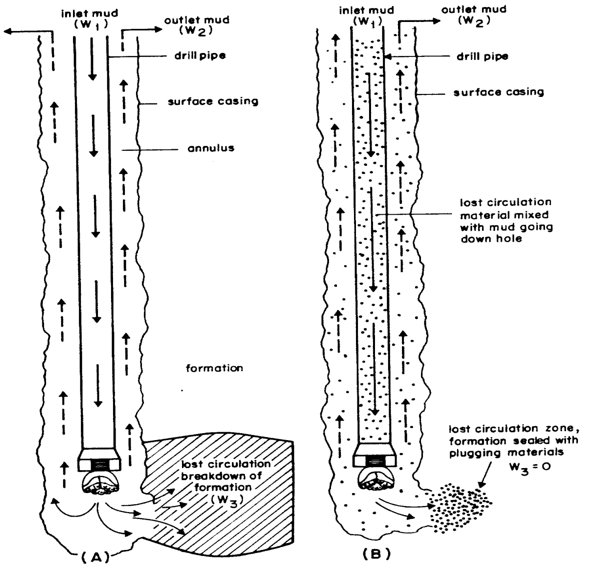

Fig. 1 Physical model of fluid circulation and lost circulation during drilling of a geothermal well.

2.1 Description of the mathematical model

The working assumptions of the model include:

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

2.2 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. 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 this work, formation vertical porosity is found by trial an error and represents an average formation porosity.

The energy and continuity equations reduce to:

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

$$\frac{1}{r}\frac{\partial\left(r\,v_r\right)}{\partial r}+\frac{\partial v_z}{\partial z}=0 \tag{2}$$

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:

$$\text{I. C.:}\quad T(r, z, t=0) = f(r, z) \tag{3}$$

$$\text{BC1:}\quad -k\left(\frac{\partial T}{\partial r}\right)_i = h\left(T_s - T_f\right) \text{ on } A_i \text{ for all } t \tag{4}$$

$$\text{BC2:}\quad \left(\frac{\partial T}{\partial r}\right)_{r=0} = 0 \text{ at } r = 0 \text{ for all } t \tag{5}$$

$$\text{BC3:}\quad v_z = W/\rho A_f \text{ at } z = 0 \text{ for all } t \tag{6}$$

$$\text{BC4:}\quad v_r = f\left(\phi, W, \rho, A_l\right) \text{ on } A_i \text{ for all } t \tag{7}$$

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 (1) through (7) define in generic form the problem posed. The functionality of T(t=0), the heat transfer coefficient h and BC4 are addressed later on.

2.2 Lost circulation modeling

Circulation losses are given by (Garcia et al., 1998b):

$$W_{fu} = W\varphi \tag{8}$$

where φ is a multiplier which takes values between 0 and 1. If $\varphi=0$ no losses occur and if $\varphi=1$ all the drilling fluid is lost to the formation. Knowing φ, the axial velocity can be calculated from equation (2). The annulus heat transfer coefficient h, at r = r_2 requires knowledge of the fluid velocity in the annulus v.

3. Simulation process

Application of equations (1-7) follows a simplified scheme of the physical well drilling system. Fig. 2 shows schematically an axial region of length Δz, the location and spacing of the radial mesh. The radii of this figure correspond to each physical region in which the well is divided. Five regions were identified as indispensable to be considered: (1) the drill pipe; (2) the drill pipe wall; (3) the annulus; (4) the well wall/annulus interface, and (5) the formation. Using this configuration, a computer code was developed. It consists of eleven subroutines of which eight are related to the mathematics of each region. A detailed description is given by García et al. (1998b).

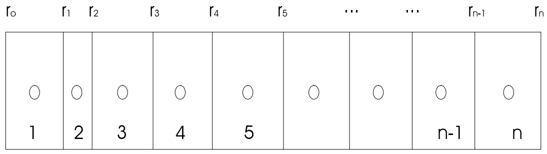

Fig. 2 Radial node distribution. r indicates the boundaries of each radial region of the well and "o" indicates the cell where the computations are performed.

3.1 Drill pipe formulation, Region 1, TINTUB

The drill pipe temperature distribution is computed here.

3.2 Drill pipe wall formulation, Region 2, TMET

The temperature distribution in the drill pipe wall is computed here- Heat transfer coefficients are calculated in modules separated modules of the code, COEFCON and COEFCONA, for the fluid in the drill pipe and in the annulus, respectively. If lost circulation is present, the annulus fluid velocity and the heat transfer coefficient are affected. These effects are properly considered in the present model, as described in Garcia et al. (1998b).

3.3 Annulus formulation, Region 3, TANU

This module estimates the temperature distribution of the annular region. The effective heat transfer coefficient h_{ef} considers the effect of porosity and is given by:

$$h_{ef} = h_{imp}(1-\phi) \tag{9}$$

where h_{imp} is the heat transfer coefficient for an impermeable wall and ϕ is the formation porosity.

3.4 Well wall/annulus interface formulation, Region 4, TINTER

The temperature distribution at the well wall/annulus interface This interface mathematically couples the formation and the flow in the annulus and should guarantee continuity of the heat flux during circulation and shut-in conditions.

3.5 Formation formulation, Region 5, TROCA

The axial and radial temperature distribution in the formation is computed here. The physical properties for this region are:

$$k_{ef} = k_a^{\phi} k_f^{(1-\phi)} \tag{10}$$

$$\left(\rho C_p\right)_{ef} = \left(\rho C_p\right)_f (1-\phi) + \left(\rho C_p\right)_a \phi \tag{11}$$

where f and a correspond to the formation and annulus fluid, respectively. If $\phi = 0$, the original equations are recovered.

3.6 Convective heat transfer coefficients

The heat transfer coefficient for laminar flow (Re < 2300) is calculated using the Seider and Tate correlation for flow inside the drill pipe and the annulus. For transitional and turbulent flow (Re > 2300) in the drill pipe and the annulus, Gnielinsky's (1976) correlation is used.

4. Model validation and applications

The present model can be used to simulate the dynamic heat transfer processes occurring in a geothermal well under construction in the presence of lost circulation. Formation temperature and average porosity (or permeability for a given fracture geometry) can be obtained by a trial and error procedure. The treatment of permeability is out of the scope of the present work since the present code does not consider Darcian flow. As a first guess, the initial temperature profile can be assumed based on the last temperature log or on static temperatures obtained via the Ascencio et al., (1994) method since this method has proven to give temperatures which are closer to the formation temperatures than the Horner method. Formation porosity is treated as homogeneous along the radial direction but heterogeneous on the axial direction. Its magnitude may be initially guessed from the lost circulation records or from measurements on drill cores.

Model tests were carried several wells (wells Az2 and EAz1 from Los Azufres geothermal field, and well LV-3 from the Las Tres Vírgenes geothermal field) and are described by Garcia et al., 1998a,b. Those results demonstrated that the effect of lost circulation on the shut-in temperature profiles can be modeled satisfactorily.

Fig. 3 compares measured and simulated shut-in temperature profiles for well H-26 from The Los Humeros geothermal field, Mexico. Also shown are static temperatures obtained with the Horner and Ascencio et al. (1994) methods and the initial temperature profile. On the left side, the circulation losses are also shown. It is seen that fluid losses affect the temperature recovery below 2000 m depth. Simulation results reproduce satisfactorily the logged temperatures for 0 and 12 hours shut-in times and are greater than logged temperatures at further times, especially between the 2000 and 2250 m depth range. This may be due to the thermophysical formation properties used since these are unknown adequately, i.e., the values for the rock volume invaded by drilling fluid, or to neglecting natural convection after shut-in. The initial temperature profile was unknown at the beginning of the simulation. It was assumed and changed until simulated and logged temperatures matched. The final temperature profile is closer in value to the static temperatures obtained with the Ascencio method than with the Horner method.

5. Conclusions

The development and application of a heat transfer model for geothermal wells with drilling fluid losses were described. The mathematical model and each of its five. Finally results of validation and previous applications tests were mentioned, and new applications are described. The results demonstrate that the effect of lost circulation on the shut-in temperature profiles can be modeled. The present model is useful since studies that account for drilling fluid losses are scarce.

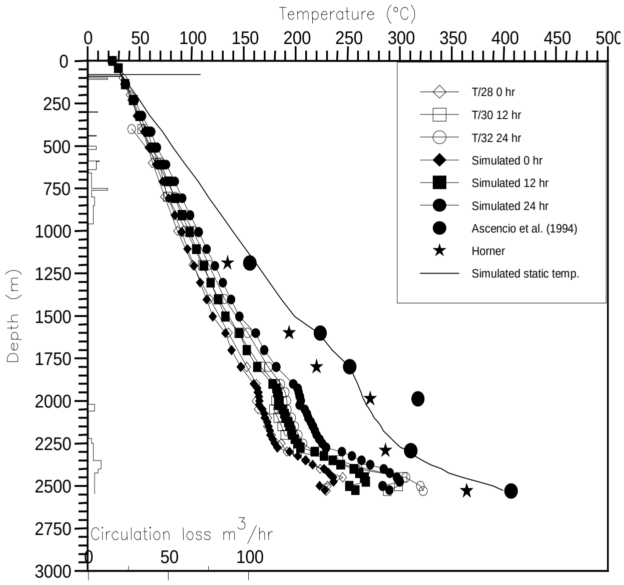

Fig. 3 Measured and computed temperature profiles of well H-26 during shut-in. The initial temperature profile is shown as a solid line on the right side of the graph.

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