Heat Transfer in the Formation Invaded by Drilling Fluid Losses from a Geothermal Well

A. Garcia-Gutierrez[1] and J. R. Ramos-Alcantara[2]

[1]Instituto de Investigaciones Eléctricas, Gerencia de Geotermia
[2]Centro Nacional de Investigación y Desarrollo Tecnológico, Depto. de Ingeniería Mecánica

Keywords

Geothermal wells, circulation losses, fluid flow, heat transfer, porous media

ABSTRACT

An analysis of fluid and heat transport in a region of the formation around a geothermal well that is invaded by drilling fluid is presented. The formation is considered as a fractured porous medium, where the liquid-phase flows through a rigid, impermeable solid-phase. 2D volume-averaged governing equations are used to describe flow of an incompressible fluid through an isotropic porous medium which is assumed to follow Darcy´s law. The thermal model is a based on volume-averaged mass, energy and momentum balances which consider the porous medium as an effective medium. A one-equation thermal transport model is derived from the averaged transport equations of the individual phases and the application of the principle of local thermal equilibrium. The total thermal effective thermal conductivity tensor is evaluated through available correlations in the literature. Finite differences and the ADI algorithm are used to solve the resulting mathematical model. Application to 3x3m portion of a geothermal reservoir around a geothermal well,, indicates that fluid velocities in the formation are on the order of 10^{-5} m/s, implying creeping flow. The temperature distribution indicates a predominant effect of heat convection at short times while diffusion dominates at longer times.

1. Introduction

When drilling oil and geothermal wells the future productive zones are associated to the depth intervals where drilling fluid is lost to the formation. One method used to locate these zones is the analysis of temperatures logs. These logs exhibit a delayed heating rate at the depths where circulation losses exist as the formation returns to its original state after fluid circulation. Another common use of such logs is the estimation of the stabilized or static formation temperature (SFT) [1]. Knowledge of the SFT has important applications in many applications, such as estimation of energy reserves, well drilling and termination, calibration of electrical logs, etc. The estimation of SFTs is done using simple or analytical approaches such as the Horner or the spherical-radial methods [2, 3]. They are widely used for their simplicity however they account for heat conduction in the formation only and ignore the thermal effects due to drilling fluid circulation losses. Numerical simulators estimate static formation temperatures [4, 5] employing macroscopic formulations, at the scale of the system under study, such that the results give an overall view of the system in terms of macroscopic variables. Simulation of circulation and shut-in typically includes conductive and convective heat transfer in the well but only heat conduction in the formation. More recently, the effects of fluid invasion into the formation have been studied [6-8], more in relation to the well completion, but little attention has been directed to the heat transfer mechanisms in the formation, and although they employ transient formulations they model circulation losses in a very simplified way. Some of the limitations include a high computational cost since the whole depth of the well is analyzed, and the complexity of properly modeling conduction and convection and fluid flow in porous or fractured media. Furthermore, previous works [6, 9, 10] validate their results with gross temperatures data measured during shut-in. It appears that so far no detailed study has been carried out on fluid and heat flow in the formation invaded by drilling fluid lost from a well. In this work, volume-averaged conservation equations of energy and momentum transport are derived using scale restrictions and applied only to the portion of the formation that is invaded by drilling fluid. The velocity, temperature and pressure fields are determined and the thermal behavior is analyzed to show the contributions of conduction and convection during shut-in. Results for well LV-3 from the Las Tres Virgenes Mexican geothermal field are presented.

2. Description of the Physical Model

Figureure 1 illustrates the physical system under study. Drilling fluid enters the drill pipe at the top, flows down reaching the drill bit near the bottom of the hole and exits and flows up the annulus formed by the drill pipe and the drilled hole. If circulation losses exist, some or all of the fluid is lost to the formation and the rests exits at the well surface. At large depths the formation is hotter than the drilling fluid and thus the fluid exits the well at a higher temperature $T_2(z_1,t)$ than that at inlet $T_1(z_1,t)$. The depth at which drilling fluid losses occur is indicated and the rightmost part of Figure.1 magnifies the part of the formation invaded by drilling fluid in order to show the numerical mesh used for the study. The mathematical formulation of these phenomena requires the establishment of hydrodynamic and thermal transport models.

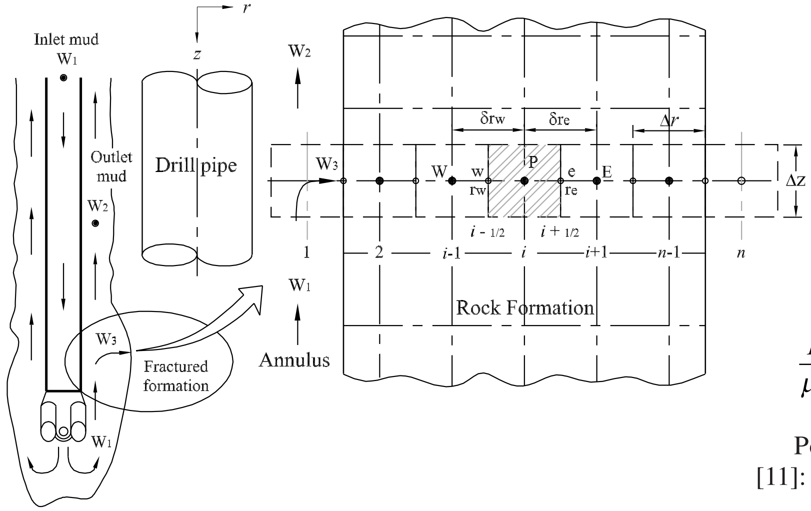

Figure 1. Model of lost circulation during drilling of geothermal wells, computational domain.

2.1 Hydrodynamic Model of the Formation

The formation invaded by drilling fluid is considered as porous or fractured medium and is constituted by two phases: the solid-phase of the porous medium considered as rigid and impermeable, the σ-phase, and the liquid phase denoted as the o-phase, considered as an incompressible fluid. Figure 2 shows a representation of the rock formation and a magnification of the selected volume to show both phases. The selected volume is known as the averaging volume which is used to derive the volume-averaged transport equations.

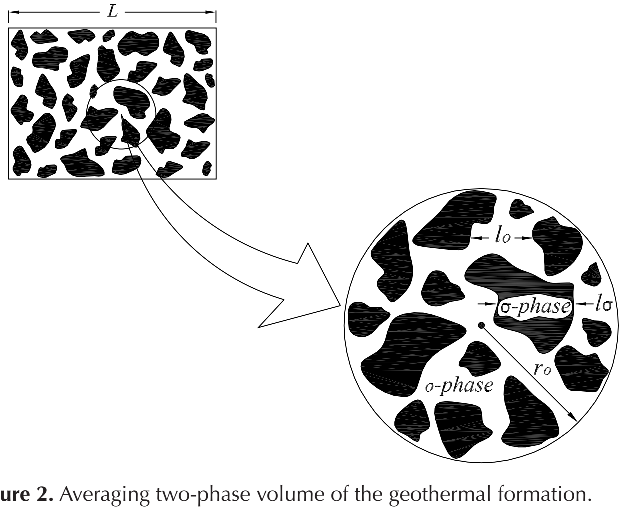

Figure 2. Averaging two-phase volume of the geothermal formation.

Considering that the flow of drilling fluid obeys Darcy´s law, the volume-averaged equations that govern fluid flow in a porous medium are given by:

$$\nabla \bullet \langle \mathbf{v}_O \rangle + \frac{q}{\rho_O} = 0 \tag{1}$$

$$\langle \mathbf{v}_O \rangle = -\frac{\boldsymbol{K}}{\mu_o} \bullet \left(\nabla \langle p_o \rangle^o - \rho_o \mathbf{g} \right) \tag{2}$$

where $<\phi>$ indicates the volume-averaged value of variable ϕ, $<\phi_o>^o$ indicates the intrinsic value of variable ϕ, ν is the velocity vector, ρ_o and μ_o are the fluid density and viscosity, q is a source term due to invasion of drilling $\boldsymbol{K}$ is the absolute permeability tensor [11] and $\mathbf{g}$ is the gravity acceleration vector. A particular solution requires the establishment of the boundary conditions BC: permeable or impermeable. The permeable BC implies loss of drilling fluid to the formation in radial direction while the second boundary condition neglects such loss. Hence, a 1D boundary problem in cylindrical coordinates can be constructed by substituting (2) into (1):

$$\frac{K}{\mu_O}\frac{\partial^2 \langle p_O \rangle^o}{\partial r^2} + \frac{1}{r}\frac{K}{\mu_O}\frac{\partial \langle p_O \rangle^o}{\partial r} + \frac{q}{\rho_O} = 0 \tag{3}$$

Permeability is obtained from the Blake-Kozeny model [11]:

$$K_o = \frac{d_p^2 \varepsilon_o^3}{180\,(1-\varepsilon_0)^2} \tag{4}$$

where d_p is particle effective diameter and ε_o is the formation porosity occupied by the fluid.

The finite volume method [12] was employed to solve Equation (3) using the computational domain shown in Figure. 1. Inversion of the resulting tri-diagonal matrix of coefficients was performed using the Thomas algorithm [12] to obtain the vector of unknown pressures. Once the pressures were obtained, the velocity field was determined.

2.2 Porosity and Permeability

In a geothermal formation invaded by drilling fluid, it is assumed that the void space of the reservoir is occupied by such fluid. Porosity values can be estimated or measured in the laboratory or inferred from electrical logs or other methods of geothermal engineering. Experimental and field inferred porosities from different geothermal fields show that porosity varies widely between 1 and 30% worldwide with mean values between 8 and 15% [13]. The porosity of Mexican geothermal fields varies from 1 to 25% [14] for igneous rocks and has typical values of 15-20% for sedimentary rocks [15]. Hence a porosity of 10% may be considered as representative of a number of geothermal fields. The permeability of a porous medium can be estimated using the Blake-Kozeny model, Equation (5) considering that the medium is constituted by an array of solid impermeable spheres [11]. However this model requires the particle or pore diameter, which for geothermal applications is of the order of 10^{-6} to 10^{-3} m [16].The particle diameter also has to fulfill the scale restrictions imposed by the volume-averaging method, shown in table 1 [17].

Table 1. Porous media length scales imposed by the volume-averaging method.

Particle or pore diameter	Averaging volume characteristic length	System characteristic length
d_p	r_o	L
$d_p < r_o$	$r_o < L$	
$10^{-10} - 10^{-2}$ m	$10^{-8} - 10^{0}$ m	$10^{-6} - 10^{2}$ m

Permeability varies widely [5, 15, 18] between 10^{-11} to 10^{-17} m^2, however values on the order do 10^{-12} m^2 are often used in geothermal reservoir engineering [5,13]. From experimental runs with particle diameters of 10×10^{-3} and porosities between 4 and 10% lead to permeability values of this order and the value used in the present model was 6.86×10^{-12} m^2.

2.3 Heat Transfer Model of the Formation

The physical system under consideration is illustrated in Figures. 1 and 2. In Figure 2 the σ-phase represents a rigid, impermeable solid phase and the o-phase represents an incompressible fluid. Since the flow is located in the pores of the formation, the transient energy equation considers 2D heat transfer by conduction and convection. The selected averaging-volume was used to develop the averaged transport equations of the individual phases, and by assuming thermal equilibrium between the phases, a one-equation volume averaged model was obtained to determine the temperature distribution in the porous formation. Application of this technique allows treatment of the heterogeneous system constituted by a static solid-phase and a fluid-phase to be treated as a homogeneous system with effective properties. The model satisfies the length scale restrictions given in Table 1. With these considerations, the volume-averaged model is obtained as:

$$\langle\rho\rangle Cp\frac{\partial\langle T\rangle}{\partial t}+\left(\rho Cp\right)_{o}\langle\mathbf{v}\rangle\bullet\nabla\langle T\rangle=\nabla\bullet\left[\mathbf{K}^{*}\bullet\nabla\langle T\rangle\right] \tag{5}$$

Simplifying Eqn. (5) to axial and radial coordinates and considering the formation as an isotropic porous medium with heat convection in radial direction,

$$\begin{aligned}&\langle\rho\rangle Cp\frac{\partial\langle T\rangle}{\partial t}+\left(\rho Cp\right)_{o}\langle v_{o}\rangle\frac{\partial\langle T\rangle}{\partial r}=\\&\frac{K_{\sigma}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\langle T\rangle}{\partial r}\right)+K_{\sigma}\frac{\partial^{2}\langle T\rangle}{\partial z^{2}}\end{aligned} \tag{6}$$

The boundary conditions of this model are: (1) the surface temperature at z=0; (2) the temperature resulting from the geothermal gradient at total depth; (3) continuity of heat flow at the well-formation interface, and (4) the temperature from the geothermal gradient as r→∞. Implicit finite differences and the ADI algorithm were used to obtain the volume-averaged formation temperatures once the flow velocities were known.

3. Results and Discussion

The system chosen for this study is a 3m by 3m portion of the formation surrounding well LV-3 from the Las Tres Virgenes, Mexican geothermal field. The initial formation temperatures are obtained from the linear geothermal gradient of 0.12 °C/m and the circulation loss amounted to 5% of the total drilling fluid flow rate. The losses occurred at 1685 m. The pressure distribution is shown in Figure 3. It is observed that when drilling fluid is losses occur, the formation is perturbed originating pressure gradients in the radial direction, which give rise to superficial velocities in the same direction. The pressure disturbance penetrates up to node 12 and extends from node 5 to node 7 in the axial direction.

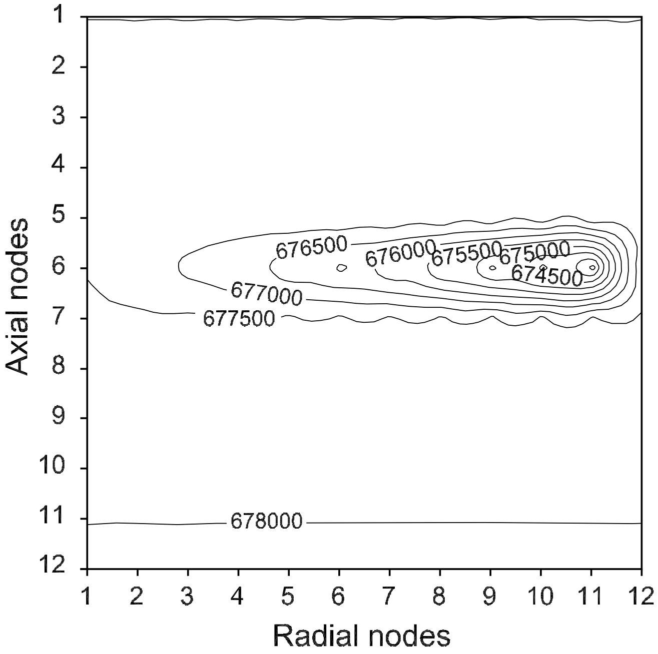

Figure 3. Pressure distribution in the formation – Contour curves.

Figure 4 shows the temperature distribution at 6 hrs circulation time. The upper parts represent hotter zones and greater depths, while the clearer areas represent colder formation zones.

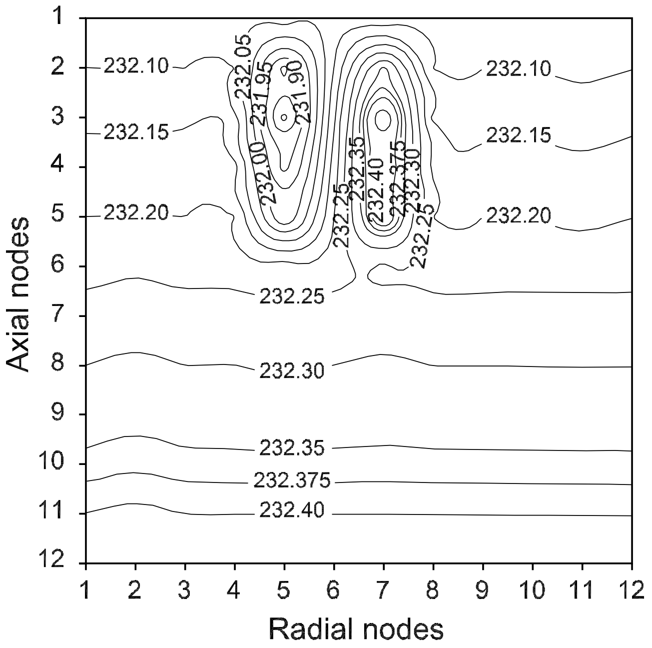

Figure 4. Temperature distribution at 6 hrs circulation time in presence of circulation losses.

4. Conclusions

A representative area of the formation surrounding a geothermal well with circulation losses effects has been studied in detail with length scale restrictions dictated by the volume-averaging method employed in this study. Pressure, superficial velocity and temperature distributions were obtained. Circulation time was varied to obtain the temperature field and the results show that the cooling effect of the formation caused by drilling fluid circulation is a key issue in understanding the dominant heat transfer mechanisms during circulation and explain why during a subsequent shut-in period, the thermal recovery of the well takes longer at the depths where circulation losses occur.

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