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Effect of Variable Rheological Properties of Drilling Muds and Cements on the Temperature Distribution in Geothermal Wells

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ABSTRACT

This paper describes a numerical study of the heat transfer phenomena occurring during fluid circulation in geothermal wells considering the temperature-dependent Non-Newtonian behavior of different drilling muds. The computational code employed is fully transient and allows estimation of temperatures of (a) the drilling fluid in the drilling pipe and the annulus, and (b) the surrounding formation. The effect of circulation losses is also accounted for. The viscosity of eleven different drilling mud formulations was evaluated experimentally as function of temperature, and the resulting numerical correlations were implemented in the computer code to evaluate the heat transfer dimensionless numbers and film coefficients, and the mud temperatures in the well as function of circulation time. The results obtained from well LV-3 of the Las Tres Virgenes Mexican geothermal field show that the computed mud temperatures are highly dependent on the particular drilling mud employed, and thus the degree of well cooling varies widely from one drilling mud to another.

1. INTRODUCTION

Knowledge of the temperature distribution of the circulating drilling fluids, the wellbore and the surrounding formation is required to predict the transient thermal behavior of the well during drilling and completion. This information is useful for correct drilling job design execution and for deciding whether drilling should be stopped or continued. This, in turn, is reflected in the final costs of the completed well. Determination of the transient temperature is a complex task since there are many influence variables which are continuously changing. Proper modeling of these phenomena requires knowledge of the thermal and transport properties of all the materials (cementing systems, reservoir and drilling fluids, rocks and pipes) involved. Rock and pipe properties are well fairly well characterized, however, the variation with temperature or composition of the transport and thermophysical properties of drilling fluids and cements is less known. Circulation of drilling fluid serves to cool and lubricate the bit, to transport the cuttings to the surface, and to control subsurface pressures, among other, and causes the drilling fluid to warm up and cool as it flows in the drill pipe and annulus. As a result, fluid circulation also produces a cooling effect of the surrounding formation. Thus, the drilling fluid becomes an important tool for predicting wellbore temperatures during circulation in geothermal well drilling process (Arnold, 1990; Beirute, 1991).

The drilling fluids used in geothermal well drilling consist of water-based muds typically (Santoyo-Gutierrez et al., 1991) and thus, some authors have used water viscosities to represent the variation of drilling fluid viscosity with temperature in heat transfer numerical studies during well drilling (Arnold, 1990; Beirute, 1991; Garcia et al., 1998a: 1998b). Evidently, this assumption could lead to significant errors in the calculation of the actual convective heat transfer coefficients (CHTC) of drilling fluids since it is known that water behaves as a Newtonian fluid (Santoyo, 1997). Thus, Santoyo et al. (2001a) characterised eleven water-based drilling fluid (non-Newtonian) formulations via dynamic measurements in a coaxial cylinder-type viscometer (Fann 50C). These measurements were then fitted to derive numerical correlations for the reliable determination of the drilling fluids viscosities as function of temperature from 25°C to 180°C. Cementing systems properties also play an important role in estimating wellbore and formation temperatures during well casing, and later on when the cement is set. Cement slurry properties are not available to the best of the authors´ knowledge, however, the thermal properties of six set geothermal cementing systems used in Mexican geothermal wells are available Santoyo et al., (2001b) and Espinosa-Paredes et al., 2002) and may be used as empirical correlations to feed numerical simulators for well temperature estimation.

Several computer programs have been developed to study the heat transfer during circulation. Some programs have used a pseudo-steady heat flow model in the wellbore with a transient heat conductive model for the formation (Raymond, 1969; Arnold, 1990; Garcia et al., 1998a). Others consider transient heat flow models in the wellbore and transient conductive models for the formation (Raymond, 1969; Wooley, 1980; Marshall and Bentsen, 1982; Beirute, 1991; Espinosa et al., 2001). Fully transient simulators that account for drilling fluid losses in geothermal wells, so far are limited to those of Takahashi et al., 1997 and García et al. (1998b; 2000). Furthermore, no comparison appears to have been published on temperatures in geothermal wells using Newtonian and non-Newtonian drilling fluids, except perhaps for the work of Espinosa-Paredes and Garcia-Gutierrez (2004) where temperatures are estimated for a constant property conventional mud and an air-water mixture.

In this work, a numerical heat transfer study of circulation and shut-in in geothermal wells considering the temperature-dependent properties of different drilling fluids (Non-Newtonian behavior) and cements is presented. Viscosity correlations of eleven Mexican drilling fluids and six correlations of thermal conductivity of Mexican cementing systems were implemented in a computer code to evaluate the resulting temperatures in the well and surrounding formation as function of circulation and shut-in time. Temperatures were estimated for the drilling fluid in the drilling pipe and annulus, and the formation. Circulation losses are also accounted for.

2. PHYSICAL AND MATHEMATICAL MODELS

Five regions are considered in the analysis. In Region 1, the fluid enters the drill pipe with known velocity and temperature. As it flows down the pipe, its temperature is determined by heat convection down the drilling pipe and heat exchange with the pipe wall. In Region 2, the pipe wall temperature is determined by heat convection between the wall and flow down in the drill pipe and up in the annulus as well as conduction in the pipe wall. 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 the annulus, the temperature is determined by heat convection, heat exchange between the annulus and the drill pipe wall, and heat exchange between the wall of the well and the annulus fluid. Region 4 is simply a boundary at the wall of the well which serves to provide for heat flow continuity between the well and the outside formation. Region 5 corresponds to the heat transfer in the formation or cement. The energy balances governing the system described above are given by four partial differential equations, which are written in generic form as:

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

where subscript i (=1, 2, 3 and 5) indicates the region where the temperature is calculated, r and z are the cylindrical co-ordinates in the radial and axial directions, respectively, T is temperature, v is the flow velocity, and ρ, Cp and k are density, specific heat and thermal conductivity of the material in each respective region. Eq. (1) and initial and boundary conditions can be written for each region described above. A detailed description of the model has been given by Garcia et al. (1998b), and will not be repeated here.

3. THERMOPHYSICAL PROPERTIES

3.1 Drilling Fluids

Fig. 1 shows the variation of drilling fluid viscosity as function of temperature for the eleven fluids mentioned above as well as a curve for water (Zyvoloski and O' Sullivan, 1980). These curves were fitted numerically to derive correlations that were implemented in the computer code. It may be observed that for some drilling fluids, viscosity increases with temperature, while for others, it decreases. A detailed discussion on this property is given by Santoyo et al., (2001a). The density, specific heat and thermal conductivity of drilling fluids vary little with temperature (less than 15%) for the present case and thus, they can be taken as constant constants using the experimental data reported for muds (Wooley, 1980; Santoyo, 1997) or approximated by the corresponding correlations for water.

3.2 Geothermal Cementing Systems

Fig. 2 shows the variation of cement thermal conductivity for the six Mexican geothermal cementing systems (GCSs) as function of temperature from 25 to 200ºC (Santoyo et al., 2001b). It is seen that except for GCS-A, thermal conductivity generally increases with temperature. The increase is small for the temperatures shown, however, it depends more on its chemical composition. The curves shown in Fig. 2 were fitted numerically and the resulting correlations implemented in the computer code to evaluate their effect on the temperature distributions.

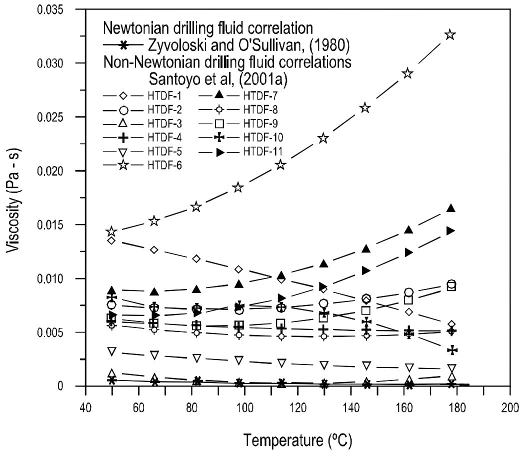

Figure 1 Variation of viscosity with temperature of the eleven Mexican drilling fluids.

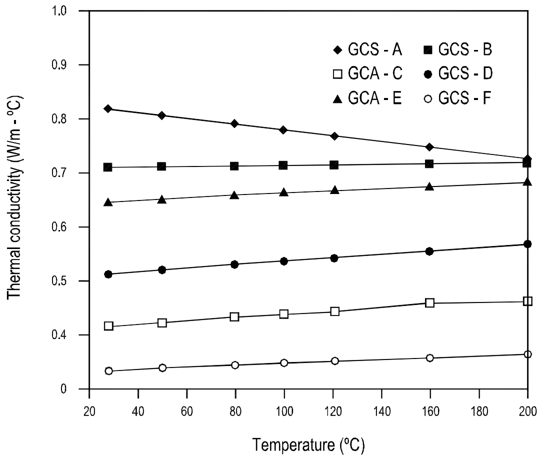

Figure 2 Variation of the thermal conductivity of six Mexican cementing systems

4. RESULTS AND DISCUSSION

The study was applied to well LV-3 of the Las Tres Virgenes, Mexico, geothermal field which had circulation losses during drilling. It is 2150 m deep and was completed in November 1994. Hole diameters are 26, 17-1/2, 12-1/4 and 8-1/2 in. Casing diameters are 20, 13-3/8 and 9-5/8 in. The liner has a diameter of 7 in and runs from about 1260 to 2133 m. Temperature profiles were obtained employing a water–air mixture and eleven high-temperature drilling fluid (HTDF) systems. For the water-air formulation, constant viscosity and thermal properties were used and its properties were calculated for a two-component mixture considering their volume proportions (García et al., 1996) while for the HTDFS's, viscosity was a function of temperature. For simplicity, the thermal properties of geothermal cement system A (GCS-A) were used.

Fig. 3 shows the temperature profile of the drilling fluid in the drill pipe at a circulation time of 0.5 hours s function for all eleven drilling fluids. Also shown is the temperature profile for case (1) described above, constant drilling fluid and cement properties. For this At this time, fluid HTDF-3 and the Newtonian fluid, case (1) or water-air mixture, are the hottest of all, while fluids HTDF-6 and HTDF-7 are the coolest, and fluid HTDF-5 attained medium temperatures.

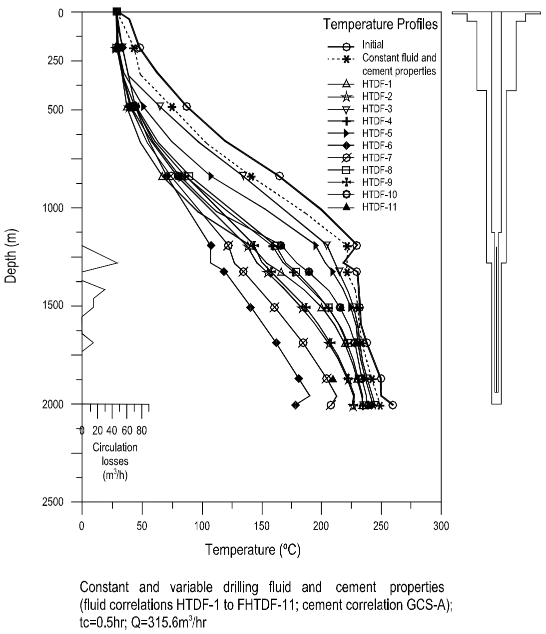

Figure 3 Temperature profiles of the eleven drilling fluids in the drill pipe at 0.5 hr circulation time.

Fig. 4 shows the temperature profiles of the drilling fluid in the annulus for all eleven HTDFs at a circulation time 2 hours. At this time, the Newtonian fluid, case (1), shows the largest bottomhole temperature and has the lowest temperature at the wellhead. This fluid remains hotter than the initial formation along most of the well length. The behavior of this fluid is closely followed by fluids HTDF-3 and HTDF-5, however, fluid HTDF-5 exhibits the largest wellhead temperature along with several other fluids like HTDF-10 and HTDG-11. Fluids HTDF-1 and HTDF-7 exhibit the lowest bottomhole temperatures but the wellhead temperature of fluid HTDF-1 is among the highest of all drilling fluids while the wellhead temperature of HTDF-7 is above the midpoint of the wellhead temperature range for all fluids. From these findings and from the shape of the temperature profiles, it can be observed that the thermal behavior of the non-Newtonian fluids is complex and varies significantly from one fluid to another. Furthermore, these profiles and the features described above, change with circulation time.

Next, a comparison of the following cases was made: (1) Constant drilling fluid and cement properties, (2) Temperature-dependent viscosity of Non-Newtonian drilling fluids (HTDF-1) and constant cement properties, (3) Temperature-dependent cement properties and constant drilling fluid properties, and (4) Temperature-dependent drilling fluid viscosity and cement properties. For case (1), a drilling fluid constituted by 70% air and 30% water was used. For cases (2), (3) and (4) the cement properties of SCG-A were used, which consists of API cement Type H, silica flour and water. The drilling fluid employed was HTDF-1 which consisted mainly of processed clays and Supercaltex and Resinex additives. Fig. 5 shows the temperature behavior of the drilling fluid in the drilling pipe as function of circulation time and depth for the four cases mentioned above. It is readily observed that the temperature variation is very similar for cases (1) and (3), constant drilling fluid and cement properties and drilling fluid constant properties with variable cement properties, respectively.

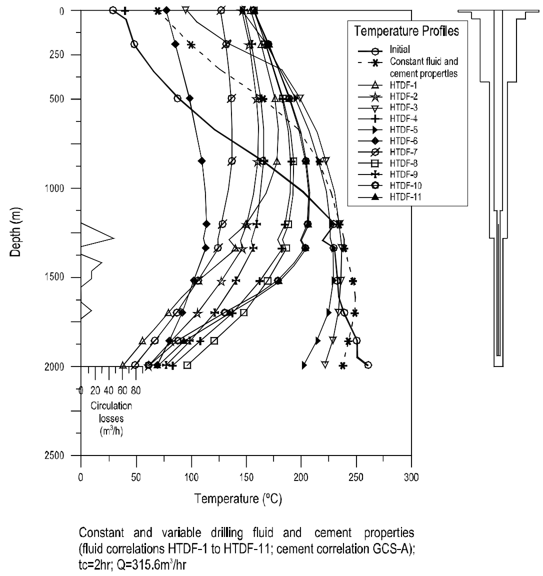

Figure 4 Temperature profiles of the eleven drilling fluids in the annulus at 2 hr circulation time

On the other hand, the results for cases (2) and (4), drilling fluid variable properties with constant or variable cement properties, are similar between themselves but are quite different from those of cases (1) and (3). From these results it is confirmed that the effect of cement variable properties has little effect with drilling fluid temperature-dependent viscosity having the largest effect. The temperatures shown in this figure decrease towards a steady state which is attained more rapidly for the case of variable viscosity of the non-Newtonian fluid. For the case of the Newtonian fluid with constant properties with constant or variable cement properties, the steady state is reached after about 4 hours at shallow depths and at about 12 hours at the bottom of the well. However, for the non-Newtonian fluid with variable properties and constant or variable cement properties, the steady state is reached at about 3-4 hours at maximum depth.

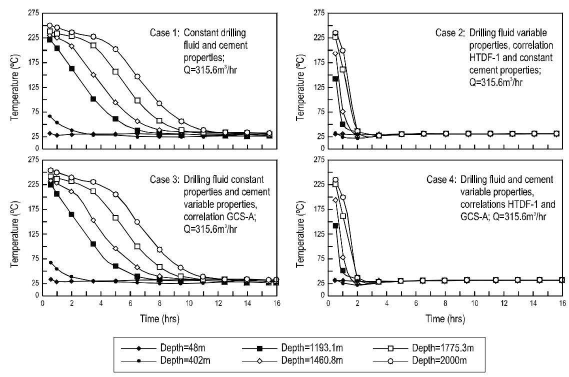

Figure 5 Transient temperature variation for cases 1 to 4 at a circulation time of 0.5 hrs and six selected depths.

5. CONCLUSIONS

A numerical study of the heat transfer phenomena occurring during fluid circulation and shut-in in geothermal wells considering the temperature-dependent Non-Newtonian behavior of different drilling fluids and the variation of the thermal conductivity of geothermal cementing systems was performed. The results obtained for well LV-3 of the Las Tres Virgenes Mexican geothermal field show that the computed drilling fluid temperatures are highly dependent on the particular drilling fluid employed, and thus the degree of well cooling varies widely from one drilling mud to another. The use of temperature dependent cement properties does not affect significantly the prediction of the temperature profiles, however a very different thermal behavior was found for a Newtonian drilling fluid represented by aerated water as compared to non-Newtonian drilling fluids.

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