TEMPERATURE DISTRIBUTION IN A WELL DURING DRILLING OPERATIONS AND MEASUREMENT OF THERMAL CONWCTIVITY OF CUTTINGS USING NEEDLE PROBE METHOD

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Intruduction

Temperature information in a well is useful in control of drilling mud properties, design of cement slurry, design of casing and selection of bore hole tools. It is more important in geothermal wells because of high temperature encountered than in oil wells. The most elusive temperature in a well is the temperature during drilling operations. Some people intended to collect extensively data on the maximum temperature in a well (1). Since a number of good theoretical papers on determining circulating temperatures have been written, they have been applied to oil well problems (2 to 6). There are apparent difference in thermal situation between geothermal fields and oil fields, and some examples are as follows:
(1) In oil country, geothermal temperature gradient is generally constant and geothermal temperature increases linearly with depth. In geothermal fields, geothermal temperature rises rapidly toa high value at a shallow depth, and thereafter increases gradually with depth. Patterns of distribution of temperature are dependent upon particular wells.
(2) In oil country, types of rocks encountered are usually sedimentary rocks, but in geothermal fields, volcanic and metamorphic rocks are mainly encountered and sedimentary rocks are intervened sometimes. It is, therfore, important that oil well practices are not directly applied to geothernwl well practices.

Our work consists of two sections: simulation of temperature distribution in a well, and measurement of thermal conductivity of cuttings. As for measurement of thermal conductivity of rock, divided bar method using cores is standard method. But in drilling of development wells, cores are taken rarely for economical point of view. In that case, cuttings are used instead of cores. There were sane previous works on measurement of thermal conductivity of cuttings (7 and 8). Needle probe method is adopted in this work for the simplicity of measurement.

Temperature Distribution

.Finite difference equations of energy balance in a drill string, an annulus and formation are solved using a SOR method. Grids in the virtical direction are made dividing well depth into a number of sections having same thickness and extended to more five divisions to set lower boundary of this system. Positions of horizontal grido are made multiplied successively a factor of two from well bore radius to outer boundary, and the outer boundary is set at an eleventh grid. The drill string and annulus are first and second grids, respectively.

A process of drilling operations consist of a number of repetition of mud circulation period and non-circulation period. It is one of a transient process. Temperature distribution changes time to time, and dose not reach stable conditions. Initial conditions varies dependent upon histry of drilling jobs. In this work, calculation starts from geothermal temperature distribution in a well, and proper length of mud circulation time and non-circulatin time is assumed. The final distribution of temperature at buildup time is taken as initial conditions of calculation of the temperature in a simulated well (Figure 1).

To test usefulness of this model, comparison is made between field data on Kakkonda test hole 206 well (760 m depth, 0.1937 m bit size) and calculated values. In Figure 2, changes of temperature of outlet mud from the well and calculated one are shown, and inlet temperature of the well and simulated one are also indicated. In actual drilling operation, cool mud is supplied into the well during trip job, but our model does not consider this factor. Simulated curve, therfore, has a tendency taken somewhat higher position, but the difference is not so significant. Further simulated curves for the same well are shown in Figure 3, in which changes of bottom hole temperature, outlet mud temperature and the maximum temperature in the well with circulation time are plotted. The inlet mud temperature is programed as follows: initial temperature is 20°C, and inlet temperature increases linearly to 65°C, and it is kept to 65 °C after one cfrculation time. Geothermal temperature distribution in the well 206 is as follows: 165°C at depth of 200 m and 197°C at depth of 500 m. Geothermal temperature rises rapidly in a shallow section, and this fact reflects on relative positions of temperatures in Figure 3. In oil well practice, bottom hole temperature is always higher than outlet temperature. But results of simulation of the well shows that the outlet temperature is higher than the bottom hole temperature and difference between the maximum temperature and the outlet temperature is very small.

A simulation of a deep well (1,500 m depth) are carried out using this model. Table 1 shows input data and some outputs are shown in Figures 4 to 7. Simplified geological columnar section and geothermal temperature in the simulated well are shown in Figure 4. Rocks are classified into two types: low thermal conductivity rocks like pumice and mudstone, and high thermal conductivity rocks like andesite tuff. To make initial conditions, mud circulation period of 12 h and buildup period of 5 h are assumed. The initial conditions of temperature is the final temperature of buildup period, and it is shown as a curve T0 in Figure 4. This temperature is assumed as the initial temperature of mud circulation process. Inlet mud temperature is simulated same as that in well 206 in Figure 3. Temperature distribution after mud circulation for 16 min, 32 min (one mud circulation time), 3 h and 75 h are shown in Figure 4 in curves of T1,T2,T3 and T4, respectively. The maximum temperatures for each circulation time are indicated by arrows. The position of the maximum temperature moves up to shallow depth at first and then moves back downward and gets to a stable place as shown in curve T4. The stable depth in the case is about one sixth of well depth from the surface. The maximum temperature after long mud circulation is somewhat higher than the outlet temperature, but these two temperature could be practiclly assumed to be same.

The maximum circulating temperature is one of the most important factors affecting choice and control of drilling mud and cement. Effect of flow rate on the maximum temperature is shown in Figure 5.

Radial temperature distributions in formation at various depth are shown in Figure 6 at the final stage of mud circulation period. Cooling effect of mud circulation does not disturbe the formation temperature beyond ten meters from the well bore.

Temperature rises in the well after stop of mud circulation are shown at various standing times in Figure 7. Our model does not contain factors of convection of heat flow and only considers conduction effects in buildup phase. Temperature rises in section of the we'll against low thermal conductivity rocks are slower but the depressions seem to diminish after long standing time. But the depression like this may occur in a small size in the actual well.

In geothermal wells, patterns of temperature distribution differ with that in oil wells. In geothermal wells, the outlet mud temperature gives a good approximation of the maximum temperature in the well. It is important for drilling practices. There is a possibility that variation of thermal properties of rocks affects a shape of temperature buildup in the well.

Thermal Conductivity Measurement Using Cuttings

Thermal conductivity of rock (Kr) is a function of thermal conductivity of rock matrix (Ks), thermal conductivity of fluid saturated pore space (Kf) and porosity of rock (ϕ).

$$Kr = f\ (Ks,\ Kf,\ \phi)$$

Many equations are proposed. For rocks having intergranular porosity, the weighted geometric mean equation is usually applied. When needle probe method is applied to cuttings, thermal conductivity of rock matrix is obtained. If the porosity of rock is known, thermal conductivity is calculated using the weighted geometric mean equation (9).

Unfortunitely, appropriate samples are not obtained in geothermal fields, so data in a well drilled in an area having ordinary geothermal temperature are shown here. Geothermal temperature in the well measured after shut-in period of six months is shown in Figure 8. Lithology changes from sedimentary rocks in upper section to metamorphic rocks in lower section and the boundary between them is located at about 1,500 m (10, 11).

Other laboratory measures thermal conductivity of cores using divided bar method. Cuttings are used to measure thermal conductivity by needle probe method in our laboratory. Comparison between these two measurements is shown in figure 8. For sedimentary rocks, there is a good consistency between data of cores and cuttings. For metamorphic rocks, there seems to be something wrong with values measured using cores, but data obtained by cuttings seem proper. Jump of values of thermal conductivity of cuttfngs at the boundary of 11thology section corresponds to decrease in geothennal temperature gradlent.

It is only one example of comparison between data of cores and cuttings. But It seems that cuttIngs is useful to estimate thermal conductIvity of formation under favorable circumstances,

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TABLE 1. WELL AND MUD PROPERTIES FOR A SIMULATED WELL

WELL DEPTH, m	1,500
DRILL PIPE OD, m	0.1143
DRILL COLLAR OD, m	0.1588
DRILL BIT SIZE, m	0.2191
SURFACE CASING OD, m	0.3397
INTERMEDIATE CASING OD, m	0.2445
DRILL PIPE LENGTH, m	1,360
SURFACE CASING LENGTH, m	350
INTERMEDIATE CASING LENGTH, m	750
FLOW RATE AT 60 spm, m³/min	1.62
INLET MUD TEMPERATURE AFTER ONE CIRCULATION,	65°C
MUD PROPERTIES:	
MUD DENSITY, kg/m³	1,080
PLASTIC VISCOSITY, kg/m·s	0.021
YIELD VALUE, kgf/m²	0.44
THERMAL CONDUCTIVITY, kcal/m·min°C	0.01
SPECIFIC HEAT, kcal/kg°C	0.[illegible]
FORMATION PROPERTIES, LOW THERMAL CONDUCTIVITY	
DENSITY, kg/m³	2,400
THERMAL CONDUCTIVITY, kcal/m·min°C	0.03
SPECIFIC HEAT, kcal/kg°C	0.2
FORMATION PROPERTIES, HIGH THERMAL CONDUCTIVITY	
DENSITY, kg/m³	2,500
THERMAL CONDUCTIVITY, kcal/m·min°C	0.054
SPECIFIC HEAT, kcal/kg°C	0.26

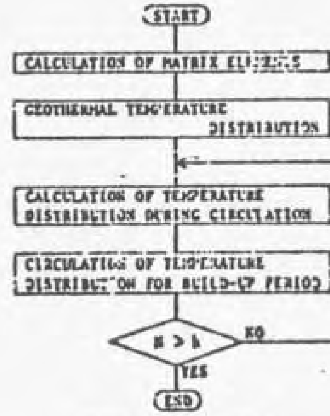

FIGURE 1. FLOW CHART

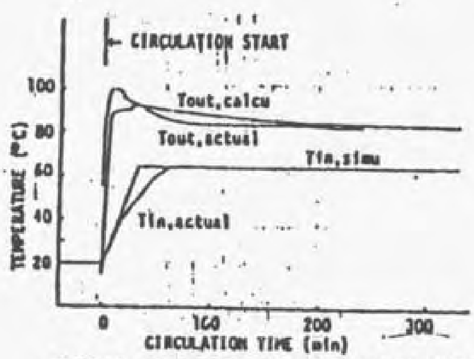

FIGURE 2. COMPARISON OF OBSERVED MUD TEMPERATURE AND CALCULATED MUD TEMPERATURE, KAKKONDA 206 WELL.

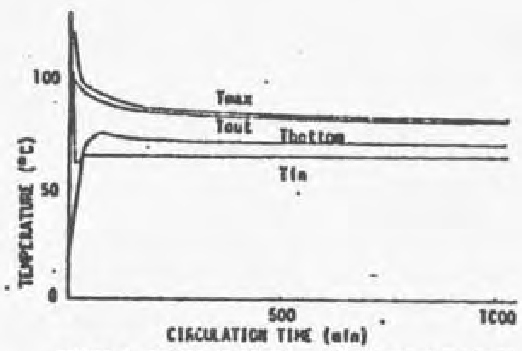

FIGURE 3. EFFECT OF TIME ON MAXIMUM TEMPERATURE IN A WELL, OUTLET TEMPERATURE AND BOTTOM HOLE TEMPERATURE FOR THE SAME WELL AS FIGURE 2 (CALCULATION).

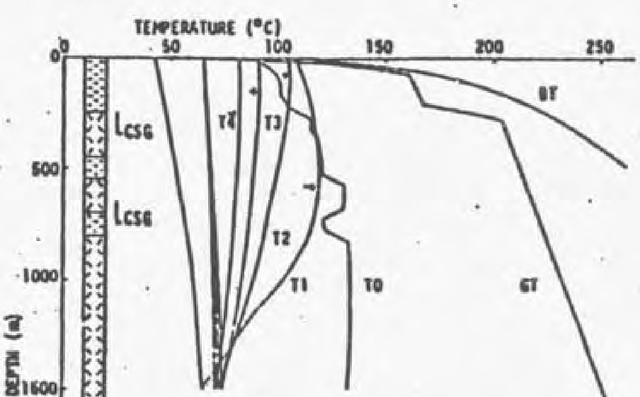

FIGURE 4. DRILL STRING AND ANNULUS TEMPERATURE VS DEPTH AS A FUNCTION OF TIME FOR A SIMULATED WELL. BT: BOILING TEMPERATURE FOR WATER, GT: GEOTHERMAL TEMPERATURE, T0: TEMPERATURE AT START OF CIRCULATION, T1, T2, T3 AND T4: TEMPERATURE AFTER MUD CIRCULATION OF 16 min, 32 min, 3 h and 75 h, RESPECTIVELY. ARROWS SHOW DEPTHS OF MAXIMUM TEMPERATURES. [::]: POROUS ROCK AND MUDSTONE, [><]: MASSIVE TUFF.

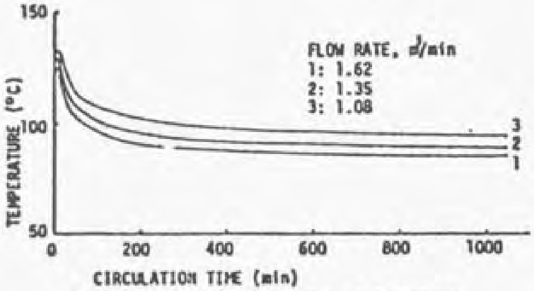

FIGURE 5. EFFECT OF FLOW RATE ON THE MAXIMUM TEMPERATURE OF THE ANNULUS FOR A SIMULATED WELL.

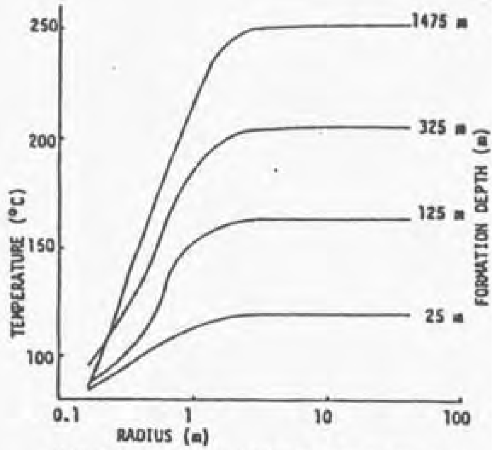

FIGURE 6. RADIAL TEMPERATURE DISTRIBUTIONS AT VARIOUS DEPTHS AT MUD CIRCULATION OF 75 h FOR A SIMULATED WELL.

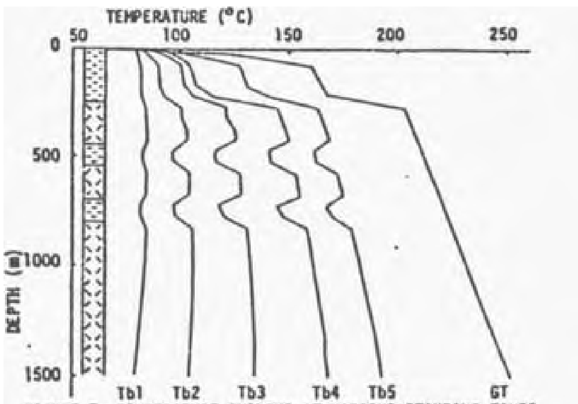

FIGURE 7. TEMPERATURE BUILDUP AT VARIOUS STANDING TIMES FOR A SIMULATED WELL. GT: GEOTHERMAL TEMPERATURE, Tb1, Tb2, Tb3, Tb4 AND Tb5: STANDING TIMES OF 72 min, 348 min, 708 min, 24 h AND 48 h, RESPECTIVELY. LITHOLOGY IS THE SAME AS IN FIGURE 4.

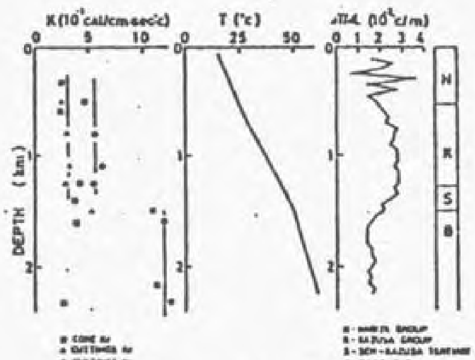

FIGURE 8. COMPARISON OF THERMAL CONDUCTIVITIES MEASURED FROM CORES AND CUTTINGS.