Normalization of Temperature Effect at Geothermal Well Drilling

Boris **B.** Kudryashov

Saint Petersburg State Mining Institute, **Saint** Petersburg, Russia, **199026**

Key words:

Thermal **insulation of** drill **pipes,** drilling **fluid cooling.**

ABSTRACT

Regulating drilling fluid temperature in drilling deep geothermal wells in many cases becomes the condition that limits not only the effectiveness but the possibility of the drilling itself. The aim of this regulation is to keep the temperature of the drilling fluid within some limits that provide normal conditions for all drilling operations, e.g., to normalize the temperature regime in the wellbore. Theoretical study of the heat exchange processes in the wellbore has shown that the temperature distribution in it can be found as the solution of the second order linear differential equation with constant coefficient based on commonly used in mining thermophysics assumptions. Analysis of the factors influencing the temperature distribution has shown that the drill pipe thermal insulating is the most effective means to normalize the temperature regime in the wellbore when drilling fluid flow rate is restricted to small values. **As** the additional agency the artificial cooling **of** the drilling fluid at the surface can be considered. Experimental tests of these recommendations carried out at Mutnovsky geothermal field in Kamchatka have shown their efficiency.

1. INTRODUCTION

The problem of the temperature regime in the drilled wellbore is to determine the temperature distribution of the drilling fluid flow in the well circulation system at any time from the beginning of circulation. Full and correct analytical solution of this problem is concerned with many mathematical difficulties. The big number of known solutions based on this kind of approach are very complicated and inconvenient in practical use. Approximate solutions based on experimental data obtained from field investigations are restricted to the conditions found during drilling perfomed.

An analytical solution based on the concept of the transient heat exchange coefficient taking into consideration the time effect on heat exchange process can be considered as the most appropriate for the practical use (Kudryashov, 1969).

2. METHODS OF TEMPERATURE REGIME CALCULATION

On the assumption that natural rock temperature is linear function of depth and that all physical properties of rocks and fluid can be considered as constants referred to the average wellbore temperature, the problem of temperature regime in the wellbore can be transferred to the solution of the second order liner differential equation with constant coefficients describing the temperature change in the descending drilling fluid flow that is a function of the temperature in the annular space. The final analytical solution for the temperature distribution in the wellbore with total depth H can be expressed as follows:

for the descending flow in a drill pipe string

$$t_1 = m_1 e^{r_1 h} + n_1 e^{r_2 h} - A + t_a + ah \qquad (1)$$

where $m_1 = -\frac{Ar_2 e^{r_2 H} + B}{E}, n_1 = \frac{Ar_1 e^{r_1 H} + B}{e}$

for the ascending flow in an annular space

$$t_2 = m_2 e^{r_1 h} + n_2 e^{r_2 h} - \frac{gG}{k_\tau \pi D}(i_1 + i_2) + T_o + oh \qquad (2)$$

where $m_2 = \frac{Ar_1 e^{r_2 H} + B\frac{r_1}{2}}{E}, n_2 = -\frac{Ar_2 e^{r_1 H} + B\frac{r_2}{2}}{e}$

where in the equation (1)–**(2)** coefficients **A, B** and E are referred to the following expression

$$A = t_a - T_o + \frac{Gc}{k\pi}\left[\sigma - \frac{g}{c}i_1 - \frac{gk}{k_\tau cD}(i_1 + i_2)\right],$$

$$B = o - \frac{g}{c}i_1 - \frac{k\pi}{Gc}\Delta t_b,$$

$$E = r_1 e^{r_1 H} - r_2 e^{r_2 H}$$

where r_1, r_2 are the roots of the equation

$$r_1, r_2 = \frac{\pi}{Gc}\left(\frac{k_\tau D}{2} \pm \sqrt{\frac{k_\tau^2 D^2}{4} + k_\tau k D}\right)$$

t_a is the temperature of the drilling fluid pumped into the drill pipe string (inlet temperature) "C; T_o is the rock temperature at the wellhead supposed to be equal to the temperature of the neutral layer, "C ; σ – geothermal gradient °C/m ;h, H, D – depth (vertical coordinate), total depth and diameter of the well respectively, m; G, c – mass flow rate, kg/s and specific heat capacity of the drilling fluid, J/(kg "C); **k** – heat transfer coefficient, W/(m °C);k_τ – transient heat exchange coefficient, W/(m^2 "C); Δt_b – the drilling fluid temperature increase at well bottom due to heat generation by the bit, "C; i_1, i_2, pressure drops in the drill pipe string inner channel and in the annular space respectively related to hydrostatic pressure in corresponding channels (dimensionless); g – acceleration due to gravity, m/s^2.

The accuracy of calculation depends on correctness in determination of all data involved in the equations (1) and (2). The temperature increase at the well bottom, for instance, must be calculated as follows:

$$\Delta t_b = \frac{N}{Gc} \qquad (3)$$

where N is the energy consumption in the process of rock fragmentation by the bit, W. Dimensionless pressure drop can be determined from the relation:

$$i = \frac{P}{g\rho H} \qquad (4)$$

where P is the pressure drop in the corresponding channel, Pa; ρ is the density of the drilling fluid, kg/m^3. All hydraulic calculation must precede the thermal ones. Heat transfer coefficient related to 1m of the drill pipe string is to calculated as follows

$$k = \frac{1}{\frac{1}{\alpha_1 d_1} + \frac{1}{2\lambda_m}\ln\frac{d_2}{d_1} + \frac{1}{\alpha_2 d_2}} \qquad (5)$$

where α_1,α_2 – heat exchange coefficients for the fluid flow in the inner channel of the drill pipe string and in the annular space respectively, W/(m^2 "C); d, d, –are the inner and outer diameters **of** the drill pipe, m; λ_m –heat conductivity of the drill pipe material, W/(m *"C)*. The values of heat exchange coefficient a in the case of drilling with water or air can be accurately calculated using wellknown criterial relations between Nusselt number Nu and Reynolds Re and Prandl Pr parameters (Mikheew and Mikheeva, 1977). Accurate relations between these parameters for the case of drilling mud are not investigated yet, therefore as the first approximations L. S. Leibenson formula can be used (Kudryashov, 1969)

$$a = 0.12 Re^{0.75} \frac{\lambda}{d} \qquad (6)$$

where λ — is the heat conductivity of the drilling mud at the average temperature in the wellbore; d is the flow channel diameter (for annular space that is equal to $d_e = D - d_2$); Re — Reynolds number determined using mud structural viscosity instead of dynamic one.

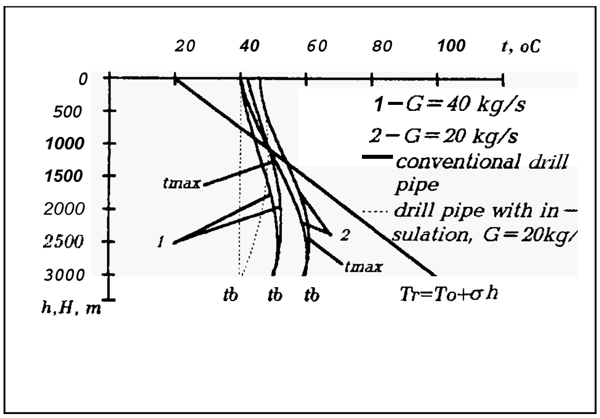
Strictly important is the determination of heat exchange intensity between the circulating fluid and surrounding rocks. It is found that sufficient accuracy in determining the value of the coefficient of the transient heat exchange is provided when it is calculated as follows:

$$k_\tau = \frac{\alpha_2}{1 + Bi Fo^{0.25}} \qquad (7)$$

where $Bi = \frac{\alpha_2 R}{\lambda_r}$ is Biot parameter; $Fo = \frac{a_r \tau}{R^2}$ is Fourier number, λ_r, a_r are referred to the heat and thermal conductivity of the rock, W/(m "C) and m^2/s, respectively; τ is the time of fluid circulation in the wellbore, s; R is the wellbore radius, m (Kudryashov, et al, 1983,1991).

3. RESULTS

Approximate theory of the drilled well temperature regime and calculational analysis based on it made it possible to explain all data obtained in the field measurements and to find the practical means of temperature regime transformation to normal conditions or its normalization. Fig. 1. represents the calculated distribution of the drilling fluid temperature in discending and ascending flows 2 hours since the beginning of circulation depending on mass flow rate and heat exchange intensity between the flows.



ℨ. 1 Calculated temperature distribution in drilled wellbore

Under normal conditions of deep well drilling with fluid flushing, the temperature increase at the well bottom dtb is very small and the highest temperature is stabilized in the annular space near the bottom, being very close to the bottom temperature tb. It was observed in the fields many times that when the mass flow rate doubles, the outlet temperature of the fluid at the wellhead is increased only by 1−2 "C. However, the bottom temperature tb decreases considerably and this was proved later by the temperature measurement. It can be explained by the decrease in the intensity of heat exchange between the two flows since doubling the flow rate causes only 60% increase of heat transfer coefficient. The temperature increase at the wellhead ts, when the viscosity of drilling mud is increased or drill pipe rotation is stopped, can be also explained by the decrease of the heat exchange between the flows of fluid, since in both cases the turbulence of the drilling fluid flow becomes less.

As calculations show the decrease of the fluid inlet temperature t_a does not effect the bottom temperature t_b causing only the decrease of the outlet temperature t_s. It may lead to an erroneous conclusion that artificial cooling of the drilling fluid at the surface does not have any effect on deep well drilling. As it can be seen from Fig. 1, the thermal insulation of the drill pipe string markedly changes the temperature distribution in the wellbore. It can be done by the laminating the inner surface of the drill pipes with polyurethane foam or other thermal insulating materials. When thermal insulation is used the bottom temperature, tb becomes close to the inlet temperature t_s and the highest temperature in the fluid flow in the annular space substantially decreases in value, and is displaced to the upper part of the wellbore which is usually cased, and thus the temperature increases in it does not present any danger. The temperature at the well outlet ts rapidly increases making the cooling of the drilling fluid at the surface more effective. All it means is that effective heat drainage of the rock mass can be achieved under described conditions.

As far as geothermal well drilling is concerned, it should be noted that the rock temperature distribution must be considered as the most important factor, since it is quite different compared with ordinary conditions of deep well drilling. In the geothermal fields at the area of recent vulcanizm the rock temperature rapidly increases with depth and the T−h relation is not linear in general case. As it was assumed by N.Gavrilov (Gavrilov, et al, 1982) the approximate relation between rock temperature and depth with regard to geothermal fields can be represented as follows:

$$T_r = T_o + 274[1 - e^{-\varphi h}] \qquad (8)$$

where φ is the exponent that can be determined by field data treatment and for the case of Mutnovsky geothermal field is accepted to be equal to 0.0014.

Using the relation (8) the equations (1) and (2) were transformed to the case of geothermal well drilling and new relationships for the temperature distribution in the wellbore were obtained. These were used for calculations accounting for the conditions of Mutnovsky geothermal field at an earlier stage of its exploration. Calculations were made for the following assumed conditions: H = 1000 m; D = 0.19m; d_1 = 0.0515 m; d_2 = 0.0635 m; rock density ρ_r = 2600 kg /m^3; rock heat capacity c_r = 1.47 J/(kg °C); rock heat conductivity λr = 1.87 W/(m "C); To = 100 °C; N = $3 \cdot 10^3$ W. Fig. 2 represents the calculated temperature distribution in the fluid for descending and ascending flows in a deep wellbore 1000 m, 1 hour since the beginning of circulation, with mass flow rates of 5 and 15 kg/s, and the inlet temperature of the fluid equal to 15 and 60 "C.

As the diagrams, show the temperature regime in the wellbore when conventional (non−insulated) drill pipes are used is determined mainly by the fluid flow rate, while the inlet temperature of the fluid is not significant. In this case the artificial cooling of the drilling fluid has a small influence on the bottom nole temperature and its effect is less in the case of low flow rate. But it causes the intensive cooling of the upper layers of rock wich is particularly important for geothermal well drilling since steam and water mixture blowouts are usually generated in this interval of these wellbore. That is why the artificial cooling of the drilling fluid is already used in practice, although it does not solve the problem since it has no influence on the bottom hole temperature. The danger of blowouts becomes significant after stops in operation for any long time even during drill string running.

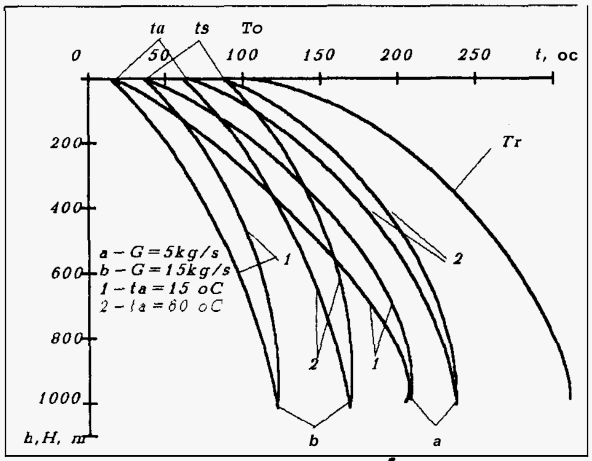


Fig. 2 Calculated temperature distribution in a wellbore at different mass flow rates of drilling fluid and inlet temperature.

As it can be seen from Fig. **3,** when thermal insulation of the drill pipe string is used, the inlet temperature of the drilling fluid, becomes the most important factor in determining the cooling of the bottom part of the wellbore, and normalization of the bit temperature conditions.

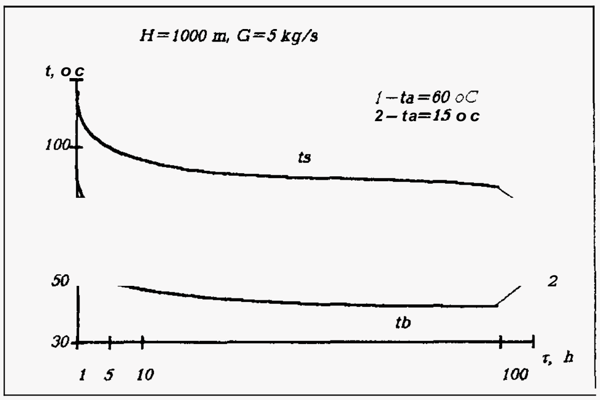


***Fig.** 3 Calculated bottom and outlet temperatures in a well drilled with thermally insulated drill pipes.*

In this case the temperature increase at the well outlet may seem to be a negative phenomena, since the danger of the blowouts becomes greater, but at the same time it makes the cooling of the drilling fluid at the surface simpler because it does not require the use of complicated and expensive cooling machines.

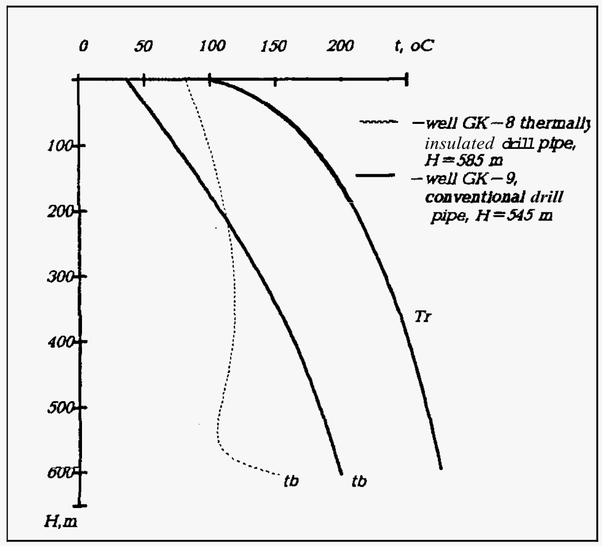
Curves in Fig. **3** show also that the bottom hole temperature and that at the well outlet stabilize very quickly, and what is more important, both temperatures become close in value that decreases the termal stress in drill and casing pipes less.

Calculation and field observation have show that using drilling mud instead of water decreases the turbulence of drilling fluid, Such flow leads to the decrease in the intensity of heat exchange and heat transfer between the two flows of drilling fluid inside the 'drill pipe string and in the annular space. But the increase of mud viscosity can lead to its thickening due to temperature effect.. Laminarization of flow by addition of such agents as sodium carboxymethyl cellulose, polyacrylamide, polymethyl– metacrylate ect. seems to be more appropriate (Thomse effect). At the same time hydraulic resistance to flow decreases by **40** to 80 percent. That is why laminarisation of the drilling fluid flow can be considered as a factor of temperature regime normalization in geothermal well drilling.

4. DISCUSSIONS OF THE RESULTS

As it follows from theory and calculations, thermal insulation of the drill pipe string seems to be the simplest and most effective means to normalize the temperature regime in geothermal well drilling. Testing this conclusion was done at Mutnovsky geothermal field where the well **GK–8** was drilled in the interval of depth from **430** m down to 585 m with the drill pipe string of **63.5** mm in diameter insulated by phtoroplastic pipes of 40mm in diameter installed inside the drill pipes. The whole thickness of the insulating pipes was from **3** to **4** mm and their thermal stability was up to 260 *"C.* The core rig of ZIF – 1200MR type was used having the pump unit 6kg/s capacity. Polymer type drilling mud of **1100** kg/m^3 density was used based on carboximethil cellulose. The drilling tool consisted of the rolling–cutter drilling bit of **190** mm in diameter, drill collar of **146** mm in diameter and **34** m long, drill collar of **108** mm in diameter and **14** m long and drill pipes of **63.5** mm in diameter. In order to control the effect of thermal insulation of the drill pipe string the data obtained from **GK–8** well drilling were compared with that obtained from drilling the well **GK–9** drilled at the same time with conventional drill pipes.

Temperature logging was done after each run of the drill bit in both wells and its results are presented at Fig. **4.**



g. ***4*** *Temperature distribution in the wellbores* ***from*** *temperature logging data.*

As it is seen the bottom hole temperature in the well **GK–8** is substantially lower than the initial rock temperature Tr at a depth of **430** m and than the temperature in the well **GK–9** while the outlet temperature in ***the*** well GK – *8* is much higher than that in the well **GK–9.** It should noted that average inlet temperature in the well **GK–8** was about 30°C higher than that in the well **GK–9.** However, even so the bottom temperature in the well **GK–8** turned out to be about twice lower (105°C instead of **193** "C at the depth **535** m]. The temperature distribution in the wellbores is presented in table 1.

Table 1. Temperature distribution in the wellbores

Well number	Depth, m												
	0	50	100	150	200	250	300	350	400	450	500	545	585
GK-9	34	52	71	89	103	120	128	139	151	160	174	193	-
GK-8	77	81	87	92	97	102	105	107	108	105	104	105	122

The increase in the outlet temperature when the thermal insulation of the drill string is used requires cooling of the drilling fluid at the surface and this also has been tested at Mutnovsky geothermal field. Since at the time of testing core drilling equipment was used with rather low pump capacity a cooling tower of film type with forced air circulation has been selected as the simplest and most compact cooling device. The tested cooling tower had the dimensions of 2'2'1.6 m and was supplied with a centrifugal fan of 0.75 m^3/s capacity driven by electric motor of 5 kW. Drilling pump of **4** kg/s capacity was used to put the hot fluid into the cooling system.

At the time of testing, the atmospheric temperature **was** from 8 to 10 °C, the temperature of the fluid at the cooling system inlet changed from 58 to 80 "C (average 69°C), that at the outlet ranged from **24** to 38 °C (average 31 °C). The temperature in the mud storage **tank** of 12 m^3 capacity was decreased by **21** °C after 1 hour of cooling system operation.

5. CONCLUSIONS

Experimental tests carried out under field conditions have proved full qualitative and very close quantitative correspondence of all calculated and observed data concerned with normalization of the temperature effect in drilling of geothermal wells. Thermal insulation of the drill pipe string can be considered the most effective means to normalize the temperature effect when the drilling fluid flow rate is restricted. The use of insulated drill pipes started at proper time and combined with artificial cooling of the drilling fluid at the surface as well as with flow rate and physical properties of the drilling fluid control make it possible to regulate the temperature regime in the wellbore in the desired direction and within presumed limits.

REFERENCES

Gavrilov, N.A, Pariisky, Y.M. (1982) *Normalization of geothermal well temperature regime in the area of recent vulcanizm. In: Research and exploration of technology in diamond drilling wells.* Proc. of VPO "Souzgeotechnika". Moscow, pp. 64–70.

Kudryashov, B.B. (1969) *Analysis, calculation procedure and problems of temperature regime regulation in a well drilled.* Proc. of Leningrad Mining Inst. v. 57, i.ss.2 pp. 80–94.

Kudryashov, B.B, Yakovlev, A.M. (1983) *Drilling boreholes in permafrozen rocks.* Nedra, Moscow, p. **282.**

Kudryashov, B.B, Chistyakov, V.K, Litvinenko V.S. (1991) *Drilling boreholes under conditions of rock phase state changing.* Nedra, Leningrad, p. 295

Mikheev, M.A, Mikheeva, I.M. (1977) *Fundamentals of heat transfer,* Energia, Moscow, p.344