Feasibility of High Temperature Penetrators in Improving Geothermal Drilling Technology

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The most important potential advantage of the new borehole drilling method - contact rock melting by means of the high-temperature penetrator - is simultaneous with driling reinforcement of the borehole walls by the creation of the vitrified melt, healing the pores, fissures and other drainage canals. It makes possible to prevent the uncontrolled outburst of overheated steam and steam-and-water mixture and lost of circulation, accompanying the traditional process of mechanical drilling.

The method of rock drilling by melting has been under both theoretical and experimental investigations of its feasibilities; testing drilling of the rock blocks on the testing units; the trials of the electrothermal drilling tools under real field conditions (Altseimer et al., 1977, Kudryashov et al., 1991).

However the geological conditions of the most geothermal fields are favorable for application of this new drilling method because they are related to the zones of volcanism and usually consist of the effusive rock having the relatively low melting points (basalt, andesites), the low density due to high porosity (tuff) and distinguished by the high natural temperature rapidly increasing with depth due to the heightened values of geothermal gradient and powerful heat flow. That is why drilling of the exploratory wells on geothermal fields is considered by the experts as one of the primary fields of effective practical application of the method of rock drilling by melting (Kudryashov et al., 1991).

The investigations of the method have been carried out by St.-Petersburg State Mining Institute (Technical University) since the eighties and based on the successful trials and application of special equipment and the technology of deep borehole drilling by melting in Antarctic Continent ice. The first stage of the investigations of the method of rock drilling by melting included a repetition of the known experiment of the American specialists and development of the basic principles of the theory of the method (Kudryashov et al., 1991).

Within the framework of the accepted in mining physics admissions using the principle of the superposition for the case of steady movement of the high temperature penetrator of the body of rotation of chain line the equation system, approximately describing the rate of drilling by melting as a function of all basic natural (geological), constructive and technological factors is obtained by analytical method.

$$V=\frac{2F\cdot\lambda_m}{\pi(R+2\delta)^2 c_m\rho_r\delta}\times\left[\frac{N_a}{\pi(R+2\delta)^2(\psi+c_r\cdot\Delta T)\cdot\rho_r\cdot V+4(R+\delta)\cdot\Delta T\sqrt{\pi\cdot\lambda_r\cdot c_r\cdot\rho_r\cdot H_c\cdot V}}-1\right] \quad (1)$$

$$\delta=\frac{1}{2}\sqrt[3]{\frac{\lambda\cdot V^2\cdot\rho_r\cdot b\left[\left(R^2+2b^2\right)\cdot sh(R/b)-2b\cdot R\cdot ch(R/b)\right]}{2\rho_m\{2p-g\cdot\rho_m\cdot b[ch(R/b)-1]\}}} \quad (2)$$

where: V=rate of drilling by melting, m/h

F=total active surface of penetrator, m^2

λ_m=melt thermal conductivity, W/(m·°C)

R=radius of penetrator top end (max), m

δ=average thickness of melt layer under penetrator, m

C_m=thermal heat capacity of melt, J/(kg C)

ρ_r=density of rock, kg/m^3

N_a=penetrator active power, W

ψ=specific heat of rock melting, J/kg

C_r=thermal heat capacity of rock, J/(kg·°C)

$\Delta T=T_f$ - Tr - difference between the melting point (phase transition temperature) and the natural temperature of rock at corresponding depth, °C

λ_r=rock thermal conductivity, W/(m·°C)

H_c=hight of cylinder of radius R, equivalent to penetrator volume, m

λ =coefficient of hydraulic resistance towards melt movement
b=chain line parameter, m
ρ_m =density of melt, kg/m^3
p=specific axial load, Pa
g=gravity acceleration

The area of the active surface of the penetrator of the body of rotation of chain line around its vertical axis is:

$$F = 2\pi b\left(R sh\frac{R}{b} - b ch\frac{R}{b} + b\right) \quad (3)$$

The coefficient of the hydraulic resistance towards melt movement in the narrow annular space between the penetrator and the rock in the first approximation can be determined as:

$$\lambda = 192\frac{v\rho_m}{R\rho_r v} \quad (4)$$

where v - kinematic viscosity of melt at average temperature, m^2/c.

The expression (4) shows that the coefficient of hydraulic resistance depends on the drilling rate and on the ratio of the rock density to the density of its melt other conditions being equal. That is why for calculation by iteration process the coefficient λ has to be calculated in accordance with eq.(4) and placed into radicand of eq. (2).

During calculations it is necessary to take into account that the numerical value of the thermal conductivity coefficient of melt λ_m through its thin layer, according to Petuchov (Kudryashov et al., 1991) has to be calculated from expression:

$$\lambda'_m=3.77\lambda_m \quad (5)$$

For calculation the confident determination of the thermal and physical properties of rock and its melt is of particular importance. We used data about basalt properties obtained in Los Alamos National Laboratory in USA (Altseimer et al., 1977).

The comparison of theoretical and experimental data of the rate of drilling by melting by the high temperature penetrator of 50 mm diameter and 75 mm high (chain line parameter b= 8.36 $\cdot 10^{-3}$ m) at constant active power N_a = 5 kW as a function of the axial load C is presented graphically in Figure1. Max deviation of theoretical data from experimental ones is not higher than 20% what can be considered satisfactory for such the complex process.

On the basis of approximate theory the computer program was developed and calculation analysis of main factors influencing on the rate of drilling by melting was made. The review of the results is presented briefly in (Litvinenko, 1995).

Theoretically proved and confirmed by the experiments the practically direct proportional dependence of the rate of drilling by melting on penetrator active thermal power and subordinate value of the axial load when drilling in the monolithic loosely bonded rocks, highly influencing on the drilling rate and the density of forming vitrified layer at low values (up to 2-3 MPa). The curve of V = f(C) becomes sloping rapidly (see Figure 1).

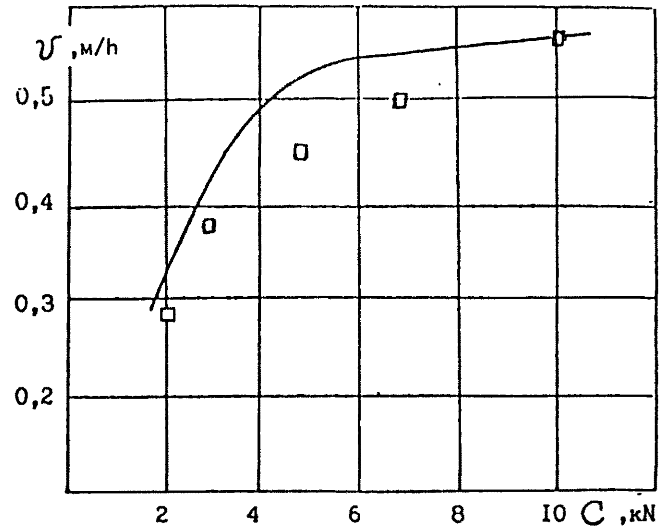

Figure 1. Experimental values and theoretical curve of dependence of rate of drilling by melting on axial load (Ø 50 mm, H=75 mm) at active power of penetrator N_a=5 kW when applied to basalt.

The axial load when drilling in loosely bonded rocks can not be considered as a serious reserve for the increase of the rates of rock drilling by melting but takes opportunity for effective application of the thermoelectrodrilling tools suspended on the weight-caryng cable or on the hose-and-cable combinations what allows to save time, work and power expenditure. This is one of the advantages of the method of borehole drilling by rock melting. In so doing the problem of a control and automation of the drilling process is simplified.

It is possible that the method of borehole drilling by melting with simultaneous pipeless reinforcement of any rocks and in any depth is the most radical solution of not only the known problems of drilling of the geothermal wells but of any boreholes, in particular, super-deep ones both with and without core selection. However, at present, especially for loosely bonded rocks this method can not be considered as alternative to traditional mechanical method and its advantages, noticed above, are potential. To realize them it is necessary to solve a problem of long-term unfailing work of the penetrators as well as to get over the technical difficulties of removal of melt redundancy from a face, its convertion into slime and transportation of the latter to the well bottom.

The results of the first stage of theoretical and experimental investigations and developments carried out by the St.-Petersburg State Mining Institute allow to conclude:

- The new method of borehole drilling is a real one and at present can be utilized in loosely bonded, porous rocks, when such advantage as simultaneous with drilling borehole reinforcement due to drying, condensation, caking, roasting and melting of the rocks plays a significant role, and the word-combination "drilling by melting" in relation to its primary application is relative and inexact expression.

- Objections against the new drilling method connecting with the saturation with water of loosely bonded rocks namely in geothermal fieldsand intended low efficiency of the high temperature penetrators as a result of their intensive cooling due to very high latent heat of vaporization (for water 2.26 $\cdot 10^6$ J/kg) are eliminated completely by the results of experiments with drilling by melting on the blocks of natural and man-made porous water-saturated and frozen rocks, specially fulfilled by LASL (Altseimer et al., 1977) and by borehole technology and drilling technics department of St.-Petersburg State Mining Institute (Kudryashov et al., 1991). In the last case experimentally proved and theoretically supported a self-simulating process of the repulsion of gravitation water by the layer of forming overheated steam, arising when drilling of loosely bonded water-saturated rock by means of the high temperature penetrator of condensing effect. The low thermal conductivity comes to the normal process of drying, condensation, caking and melting of rock in contact with high temperature surface of the penetrator made from heat resistant constructional materials stable towards oxidizing under conditions of the drilled borehole.

- Utilization of the known heat-resistant materials used by the precursors (pyrolytic graphite, wolfram-rhenium alloy, molybdenum-rhenium alloy) for the purpose of a wide and successful introduction of the new method has no prospects because these materials require continuous supercharging of inert gas (e.g. helium) into the penetrator for prevention the oxidizing process what complicates and rises in price the drilling process.

On the second stage of the investigations, thanks to conversion of the Russian defense industry the new heat-resistant constructional materials of two types-the constructional materials on the basis of carbon and silicon and ceramics on the basis of caked oxides were found. Fabricated from the new materials of the first type penetrators and generator of heat of small diameter allowed to investigate the high temperature influence on the sedimentary rocks which are typical for oil and gas deposits (argillite, aleurolite, limestone, dolomite, sandstone). Their thermal transformations (Litvinenko, 1995) were studied, the possibility of drilling by the high temperature penetrators (up to 2000°C) in any variety of these rocks, including clay-containing and carbonate. Using the specially built testing unit and the boreholes models the principle of the pipeless reinforcement of the loose and fractured rocks due to thermomechanical treatment (Litvinenko, 1995) was studied.

It is established that when drilling in the loose, loosely bonded, porous rocks specifically water-saturated and frozen ones by the high temperature penetrator with the relatively cool active end the thinning and softening of the rock due to drying (evaporation of gravitation water), dehydration (sublimation of chemically bonded water), burning of organics, decomposition of carbonates attended by isolation of CO_2, then condensation, caking and partial melting of the internal surface of the condensed and thermal transformed borehole walls take place. The method and the device for borehole drilling in condensed rocks simultaneous with ecological clean pipeless reinforcement (patent of RF N 2038475, patent of USA N 5479994) is substantiated.

The second stage of the investigations includes also the development of the method and the means for pipeless reinforcement of the boreholes, sunk by traditional mechanical method, on the basis of high temperature influence on the rocks constituting the borehole walls and of utilization of the relatively easily melted tamping materials.

In the first case the problem comes to the creation of the high temperature generator of heat (HTG) that can evaporate the surrounding fluids in the insulated by the packers borehole interval and exert mechanical and thermal influence on the borehole walls, intensity of which is sufficient for consolidation and melting of the rocks. Developed in cooperation with Drilling Technics Institute the prototype ÂÒÃ-1 (HTG-1) in November 1993 was undergone a trial under various regimes in the wells specially drilled by mechanical method on proving ground in Kavgolovo. In so doing the satisfactory results of the borehole walls reinforcement took place when high temperature influence of the generator of heat were attended by mechanical condensation of the loose rock.

The complex conditions of the incompressing rocks broken by large joints or cavernous the method and the device for the continuous or periodical pipeless reinforcement of the borehole walls by relatively easily melted tamping materials (patent of Russia # 2057901) was substantiated. The proper choice of the easily melted material (e.g. sand with vitrifying admixture) can provide not only with high mechanical strength and durability of the wall reinforcement without use of the steel and other casing pipes (especially in high aggressive medium of the mineralized hot waters), but with complete ecological uncontamination of the reinforcement. The feasibility of the reinforcement of the borehole walls with help of the easily melted materials stable towards corrosion and decomposition in place of the casing pipes is a sufficient reserve of increase of the drilling productivity and decrease of the borehole cost in conformity with the conditions of the geothermal fields.

Even under the most unfavorable conditions when the reinforcement of the separate intervals of the unstable rocks or the insulation of the absorbing layers in the deep boreholes with help of the easily melted tamping materials and the packing heat penetrator can be considered as temporary, this method gives opportunity to simplify the borehole design and to decrease the initial drilling diameter. In so doing the hoisting capacity, power and mass of the drilling device are decreased, significant reduction of expenditure of the casing pipes, tamping cement and lubricants are provided, work safety is increased, the labor-consuming character of works connected with the complex reinforcement technology in the geothermal fields is decreased.

The advantages of the reinforcement method and the insulation of the separated intervals of the geothermal boreholes with help of the relatively easily melted tamping materials can be utilized for observance of the recommendations concerning normalization of the temperature regime of drilling developed in St.-Petersburg Mining Institute (Kudryashov, 1995).

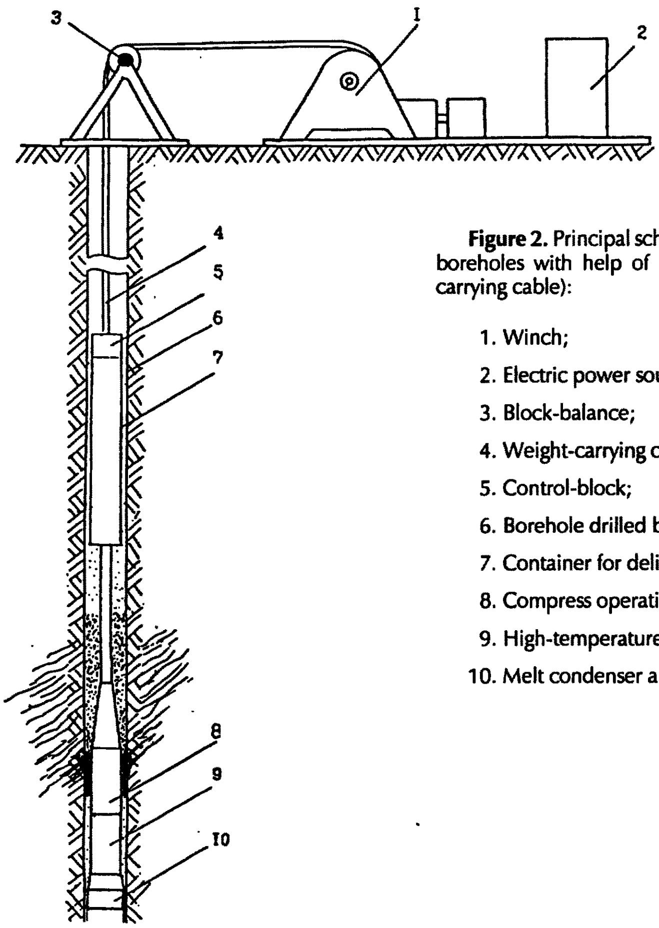

Figure 2. Principal scheme of pipeless thermomechanical reinforcement of boreholes with help of easily melted binding material (version of weight-carrying cable):

1. Winch;
2. Electric power source
3. Block-balance;
4. Weight-carrying cable;
5. Control-block;
6. Borehole drilled by traditional mechanical method;
7. Container for delivering granulated easily melted binding material;
8. Compress operating instrument;
9. High-temperature generator of heat;
10. Melt condenser and crystalizer-molder of boreholes

Initially the most chip and available tamping materials containing sand as a filler (to 80-90% of mass) and bitumen and organic substances -resins and plastics-as an easily binding material were tested. The important advantage of the tamping materials undergone the test is the low melting point thanks to which the scarce and expensive heat-resistant constructional materials are not required for the packing thermal penetrator manufacturing. However the significant disadvantage of the easily melted tamping materials is the insufficient mechanical strength of hardened condition and hence low durability of the reinforcement. Secondly, these materials do not satisfy the modern requirements of the ecological uncontamination of the pipeless borehole reinforcement because the organic substances (resins and plastics) are decomposed for a time with unpredicting consequences.

For mentioned above reasons the sandy-clay and sandy-cement mixtures under various degrees of drying were tested. In the first case the thermal influence of the packing penetrator provides with caking and baking of the condensed and dried when packing mixture with formation of the durable and stable material like ceramics that binds in monolith the broken by joints rock. In the second case the thermal influence of the penetrator is conductive to acceleration of mixture seizing with formation of the concrete stone.

By fulfilled experiments is proved the prospect of application of a number of variety of sand completed by soda, potash what in combination with thermal influence of the packing penetrator provides with formation of vitrified mass distinguished by durability and complete ecological uncontamination. However in the last case the temperature of the active surface of the penetrator is supposed to be 1000-1200°C, what requires utilization of significantly heat-resistant and stable towards oxidation constructional materials.

As far as the possibility of utilization of the relatively unexpensive new constructional heat-resistant materials for penetrator manufacturing is confirmed (Litvinenko, 1995), the developments in this direction have been continued.

The investigations of mechanism of joints filling with the melted materials (paraffin, bitumen, sandy-bitumen mixtures), fulfilled using the model of the fractured borehole part with help of the specially made models of the packing penetrator of pressing and drawing type, allowed to draw a conclusion about the method of the reinforcement of the fractured layers and insulation of the absorbtional zones in the boreholes sunk by traditional mechanical method with help of the easily melted tamping materials. As it turned out, under influence of the thermal penetrator from top to bottom on the granulated easily melted material filling the fractured part of the borehole the generated melt is easily squeezed up the penetrator and fills badly the joints and drainage canals in the borehole walls. The cause is that the less viscous layers of the melt, coming in contact with the active surface of the thermal penetrator, move alongside this surface up, what the natural convection is conductive to, furthermore the natural fluids filling the joints prevent penetration of the melt into the joints. A contrary picture is observed when drawing the thermal penetrator upwards via the layer of the granulated easily melted material with help of the bar or cable. In this case, firstly, the gradual warming-up of the easily melted material above the penetrator due to the natural convection take place, the melt flows into the joints under influence of the gravity and, possessing the large density, the melt forces any fluids out of the exclusive joints. In so doing the fluids can easily go up via the layer of not melted granulated easily melted tamping material. As a result the high quality filling of closed with the borehole joints with generation of the even and smooth casing from the hardened material on the borehole walls takes place.

The method and device for the pipeless reinforcement of the borehole by the easily melted materials can be described schematically:

The packing thermal tool (Figure 2) with the container 7 for granulated binding material in its top part is sunk with help of the pipes, containing cable, or weight-carrying armoured electrocable 4 into the zone requiring the reinforcement or insulation. By electrosignal from above the granulated easily melted material from container 7 get into the interval of the borehole 6, requiring the reinforcement or insulation. The generator of the heat feeded by the electric power source 2 through electrocable 4 is warmed and the packing tool with help of the winch 1 and the block- balance 2 begins to move positively to the borehole mouth. During this movement the reinforcement or insulation of the interval of 5-7 m takes place. The reinforcement procedure are repeated when the intervals are more powerful. The effectiveness of the method is confirmed in the not deep boreholes drilled at the drilling training site.

At present the investigations and developments within the framework of creation of the durable high temperature penetrators on the bases of the new constructional heat-resistant materials and practical mastering of the method of the pipeless reinforcement of the separate intervals of the deep boreholes, including geothermal ones, have been fulfilled by St.-Petersburg State Mining Institute in cooperation with the specialists of Los Alamos National Laboratory of California University, USA.

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