Mathematical modeling of rocks plasma disintegration process at borehole reaming

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Mathematical modeling of rocks plasma disintegration process at borehole reaming

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Abstract. The mathematical model of thermal disintegration of rocks during the reaming of boreholes, which takes into account the compatibility of the thermogas dynamic problem for a high-temperature heat transfer agent and the thermal problem for the rock heated by this heat transfer agent, has been developed. The mathematical model is based on the laws of conservation of mass, quantity of motion and energy and takes into account the dependences for determining the thermal stresses and the temperature of brittle fracture of rocks. As a result of solving the equations of the mathematical model, the temperature distribution in the rock mass (magnetite quartzite) during heating in the process of borehole plasma reaming and productivity of the borehole plasma reaming process are obtained. Calculated and experimentally determined productivity of the process of plasma reaming of the borehole were compared.

1. Introduction

The main directions in improving the efficiency of borehole thermal reaming technologies are the use of a plasma thermal tool that is more advanced in terms of operational characteristics, which is restrained by an insufficient theoretical basis in the field of heat exchange and gas dynamics of high-temperature heat transfer agents, in particular, plasma, during their interaction with the material of the rock massif.

Analysis of the existing methods of analytical determination of the parameters of the process of rocks' thermal disintegration during the reaming of boreholes showed that they are limited to a separate solution of the linear one-dimensional equations of motion, thermal conductivity and determination of the thermal stress state. This statement of the problem is approximate due to neglecting the compatibility of the thermogas dynamic problem for a high-temperature heat transfer agent and the thermal problem and the problem of thermoelasticity for the rock heated by this heat transfer agent. Creation of an improved mathematical model of thermal disintegration of rocks during borehole reaming with the use of plasma thermal tools, establishment of regularities and determination of parameters of the technology of thermal disintegration of rocks is relevant and important for the mining industry.

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The Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine has accumulated significant scientific and practical experience in the creation of thermal tools for the rock's disintegration. The possibility of continuous reaming of boreholes or obtaining in them chamber cavities of different cross-sectional shapes at the required depth with a non-rotating plasmatron has been established [1]. Through experimental studies of the thermal rocks disintegration technology, its high performance for rocks with different physical and mechanical properties is shown [2]-[4].

At the current stage of scientific and technical progress, the determination of the parameters of the rocks thermal disintegration process during the borehole reaming, as well as the search for optimal modes of operation, the creation of more effective technologies of thermal disintegration are impossible without fundamental research in the field of heat exchange and gas dynamics of high-temperature heat transfer agents, in particular, plasma, when interacting with rock material. Mathematical modeling with the use of modern methods of computational mathematics and computers [5]-[7] allows to understand the patterns of processes and to make efforts to improve existing and create new energy-efficient equipment.

The purpose of the work is mathematical modeling of the rocks thermal disintegration during the borehole reaming using a plasma thermal tool, determination of productivity and its comparison with experimental data of technology of plasma reaming of through boreholes.

2. Methods

2.1. Physical representation of the rocks plasma disintegration process during the borehole reaming

As a working body of the borehole reaming unit (figure 1), a plasmatron 1 is used, where an electric arc heats the gas flow 2 to a temperature of $(3...10)\cdot 10^3$ K. Before the process of borehole reaming, the drilling of a through downhole borehole 3 with a diameter of $D_0 = 105$ mm and its opening on the underlying horizon 4 are preliminary used.

Reaming begins with lowering the plasmatron to the horizon below, closing and sealing the top of the borehole and starting the plasmatron.

At the outlet of the plasmatron, a high-temperature gas jet is formed, which heats the surface of the borehole due to convective heat transfer and radiation. Disintegration of the borehole rock is caused by cyclic heating, which creates temperature gradients and, as a result, thermal stresses that exceed the bound of strength of the rock. Fracture products are removed from the borehole by gravity with the help of natural gravity method to the lower horizon.

During the interaction of gas in the borehole in the direction of flow, the rock surrounding the borehole is heated axially and radially, and the gas is cooled accordingly. In the process of borehole reaming, the plasmatron gradually rises. The duration of cyclic disintegration depends on the physical and mechanical properties of the fractured rock, borehole diameter and thermodynamic properties of the rock.

2.2. The mathematical model

The mathematical model of plasma reaming of boreholes is based on the laws of conservation of mass, quantity of motion and energy and takes into account the dependences for determining the thermal stresses and the temperature of brittle fracture of rocks. The system of equations that reflects these laws and dependencies taking into account axial symmetry is of the form:

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial}{\partial x}(\rho u) = 0, \tag{1}$$

$$\frac{\partial(\rho u)}{\partial \tau} + \frac{\partial}{\partial x}(\rho u u) = -\frac{\partial P}{\partial x}, \tag{2}$$

$$\rho \frac{\partial h_{\mathrm{g}}}{\partial \tau} + \frac{\partial}{\partial x}(\rho u h_{\mathrm{g}}) = \alpha (T_{\mathrm{sg}} - T_{\mathrm{g}}) \cdot \frac{U}{f}, \tag{3}$$

$$\rho = \frac{P}{R_g T_g}, \tag{4}$$

where u – longitudinal speed of movement of the plasma-forming gas, m/s; $U = \pi \cdot D$ – perimeter of the borehole, m; D – diameter of the borehole, m; $h_g = C_p \cdot t_g$ – specific enthalpy of the plasma-forming gas, J/kg; C_p – specific isobaric heat capacity of the plasma-forming gas, J/(kg·K); t_g – gas temperature, °C; α – coefficient of heat transfer from the plasma-forming gas to the borehole surface, W/(m^2·K); ρ – density of plasma-forming gas, kg/m^3; T_{sg} – borehole surface temperature, K; T_g – the temperature of the plasma-forming gas in the current section along the length of the borehole, K; $f = \pi \cdot D^2/4$ – cross-sectional area of the borehole, m^2; P – the pressure of the plasma-forming gas, Pa; R_g – gas constant of plasma-forming gas, J/(kg·K); τ – time, s; x and r – current coordinates along the axis and radius of the borehole, m.

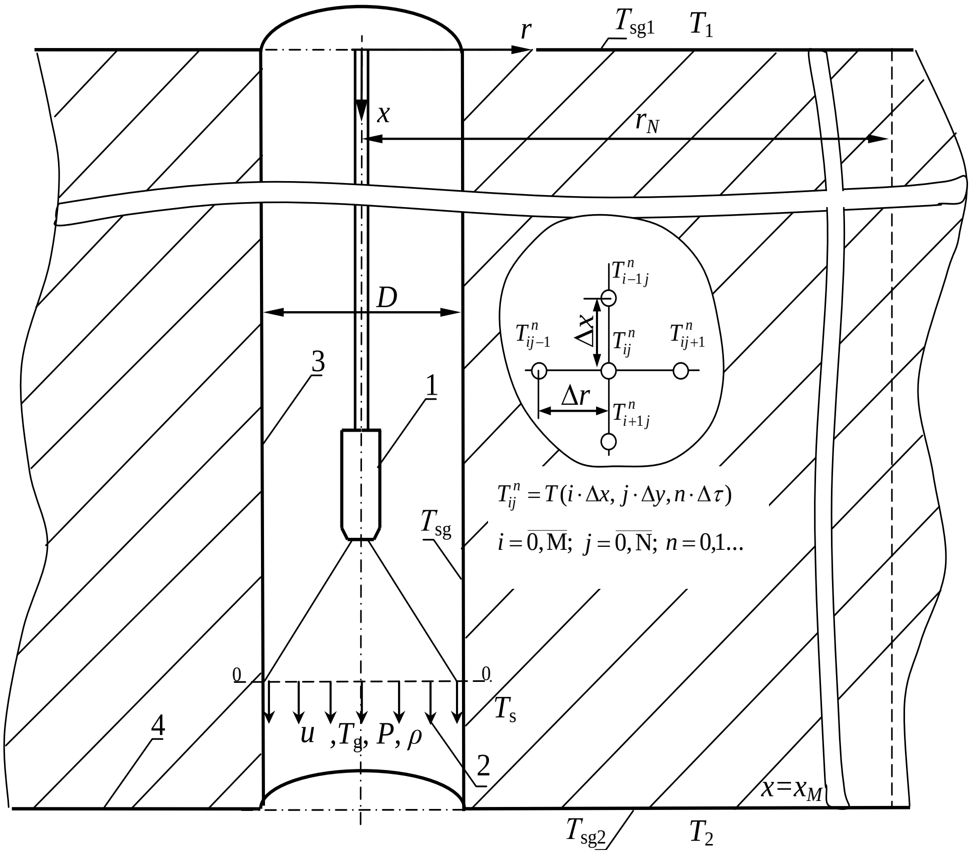

Figure 1. Scheme for calculation.

The heat transfer coefficient α from the plasma-forming gas to the inner surface of the borehole is determined depending on the Nusselt number and the thermophysical properties of the plasma-forming gas in the current section along the depth of the borehole:

$$\alpha = Nu \frac{\lambda}{D},$$

where λ – thermal conductivity of the plasma-forming gas, W/(m·K); $Nu = 0.022 \cdot Re^{0.8} \cdot Pr^{0.43} \cdot \varepsilon_l$ – Nusselt number; $\varepsilon_l = 1.38 \cdot (x/D)^{-0.12}$ – correction factor [8]; $Pr = \mu C_p / \lambda$ – Prandtl number; μ – dynamic viscosity of the plasma-forming gas, Pa·s; $Re = u D \rho / \mu$ – Reynolds number.

The initial and boundary conditions for (1)-(4) are the known parameters of the gas at the initial moment of time, which fills the borehole, and the parameters of the gas at the outlet of the plasmatron:

$$\text{at } \tau = 0,\ x = 0 \quad T_g = T_{g0},\ u = u_0,\ P = P_0,$$

where T_{g0} – the initial temperature of the plasma-forming gas at the entrance to the calculation area, K; u_0 – its initial velocity, m/s; P_0 – initial pressure, Pa.

To calculate the temperature field in the rock massif T_s, the two-dimensional unsteady heat conduction equation in cylindrical coordinates is used:

$$\rho_s C_{ps} \frac{\partial T_s}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_s r \frac{\partial T_s}{\partial r}\right) + \frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T_s}{\partial x}\right), \tag{5}$$

where ρ_s – density of the rock massif, kg/m^3; C_{ps} – isobaric heat capacity of the rock massif, J/(kg·K); λ_s – thermal conductivity of the rock massif, W/(m·K); T_s – temperature of the rock massif, K.

The differential equation (5) was supplemented with initial and boundary conditions:

$$\text{at } \tau=0 \quad T_s = T_{s0},$$

$$\text{at } r = D/2 \text{ and } 0 \le x \le x_M \quad \lambda_s \frac{\partial T_s}{\partial r} = \alpha\left(T_{sg} - T_{gm}\right),$$

$$\text{at } x = 0 \text{ and } D/2 < r \le r_N \quad \lambda_s \frac{\partial T_s}{\partial x} = \alpha_1\left(T_{sg1} - T_1\right),$$

$$\text{at } x = x_M \text{ and } D/2 < r \le r_N \quad \lambda_s \frac{\partial T_s}{\partial x} = -\alpha_2\left(T_{sg2} - T_2\right),$$

$$\text{at } r = r_N \text{ and } 0 \le x \le x_M \quad \frac{\partial T_s}{\partial r} = 0\,;\ T_s \approx T_{s0},$$

where T_{gm} – the average temperature of the heat transfer agent in the cross-section of the borehole at the length x, K; T_1, T_2 – air temperature on the upper and lower horizons, K; α_1, α_2 – heat transfer coefficients on the upper and lower horizons, W/(m^2·K); T_{sg1}, T_{sg2} – temperature on the rock massif surface in the upper and lower horizons, K.

The temperature of the rock massif surface T^* at the moment of disintegration according to the mechanism of stability loss:

$$T^* = \frac{2\sigma_c(1-\mu)}{\beta E},$$

where β – linear thermal expansion coefficient, 1/K; E – Young's modulus, Pa; μ – Poisson's ratio; σ_c – tensile strength of the rock massif for uniaxial compression, Pa.

Table 1 shows the values of β, E, μ, σ_c [9] and the temperature of peeling (thermal disintegration) T^* for different types of rocks, which is obtained by calculation.

Table 1. Values of β, E, μ, σ_c and T^* for different types of rocks.

Rock type	$\beta \cdot 10^{-6}$, 1/K	E, GPa	μ	σ_c, MPa	T^*, °C
Basalt	4…5	30…50	0.22	80…300	560
Diorite	6…7	35…70	0.25	100…200	230
Dolomite	11…13	50…100	0.20	50…150	95
Gneiss	5…9	20…70	0.22	150…200	500
Granite	8…14	20…70	0.20	100…250	320
Marble	7	30…80	0.30	60…200	250
Quartzite	11…15	20…100	0.25	140…300	230
Sandstone	10…13	7…40	0.27	30…250	550
Slate	6	40…90	0.15	10…200	140…280
Tuff	3…5	1…10	0.10	10…30	640

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To determine the thermophysical properties of the plasma-forming gas and the rock massif depending on temperature, the data were approximated according to known reference sources [10]-[11].

Thus, having solved the equations system of the mathematical model (1) - (5) with the corresponding initial and boundary conditions, we determine the temperature of the rock massif. At the points where the temperature T^* is reached, the rock massif disintegrates.

To solve the equations of the mathematical model, the well-known numerical method of grids [12] was used, when a calculation grid with a step in coordinates Δx, Δr, $\Delta \tau$ is superimposed on the calculation area (figure 1). The searched velocity and temperature functions are replaced by the corresponding grid functions, which are defined at the grid nodes. Differential equations (1) - (5) and their boundary conditions are replaced by corresponding discrete analogs. The resulting system of algebraic equations was solved by the iterative method.

As a result of the next iteration, the temperature field in the rock massif is obtained. At the points where the temperature $T_{ij}^n = T^*$ is reached, the disintegration of the rock massif occurs and the volume of the borehole, where the gas moves, increases accordingly. This leads to a corresponding change in the grid and boundary conditions and repetition of the calculation.

If the coordinates where the temperature reaches the disintegration temperature are known, the volume of the destroyed rock massif at each time step is determined by the formula:

$$\Delta V_{i,j} = 2\pi\left(r_{j-1} - r_j\right)\Delta x_i .$$

For the entire calculation time, the volume of destroyed rock is determined as the sum:

$$V = \sum_{i,j}\sum_{\tau}\Delta V_{i,j} .$$

The total productivity of the borehole reaming process is defined as the volume of destroyed rock during the time of disintegration $Q=V/\tau$.

3. Results and discussion

According to the reaming technology, the plasmatron is lowered to a depth of 4.6 m, after that the process of borehole reaming begins. After appropriate time intervals (influence time), the plasmatron rises and gradually heats the entire area. During the calculation, the time intervals and the height of each lift were chosen so that the total influence time was the same and equaled 14400 s, so the energy consumption for the reaming process was the same.

The figure 2 shows the temperature distribution in the rock massif (magnetite quartzite) during heating in the process of plasma reaming of the borehole at the moment when the borehole is expanded to a diameter of D_k = 300 mm. We can see that with increasing initial gas temperature, the value of temperature gradients in the rock massif during plasma reaming of the borehole increases.

The figure 3 shows the change of the current borehole diameter by depth. According to the calculation results, the unevenness of profile of borehole, which occurs as a result of disintegration, significantly decreases in the direction of the outlet hole. The longer the exposure time at each step is, the greater the fluctuations of the diameter in the upper parts of borehole are. The uneven velocity causes an additional dynamic effect on the rock massif and intensifies the heat exchange between the heat transfer agent flow and the borehole wall.

Table 2 shows the productivity of the process of plasma reaming of the borehole from the initial diameter D_0 = 105 mm to the final D_k in magnetite quartzite, determined experimentally in industrial conditions in the mines of Kryvbas [13] and calculated using the developed mathematical model.

The table shows that the calculation error does not exceed 26 %. Given the complexity of conducting experiments in industrial conditions, the error can be considered satisfactory.

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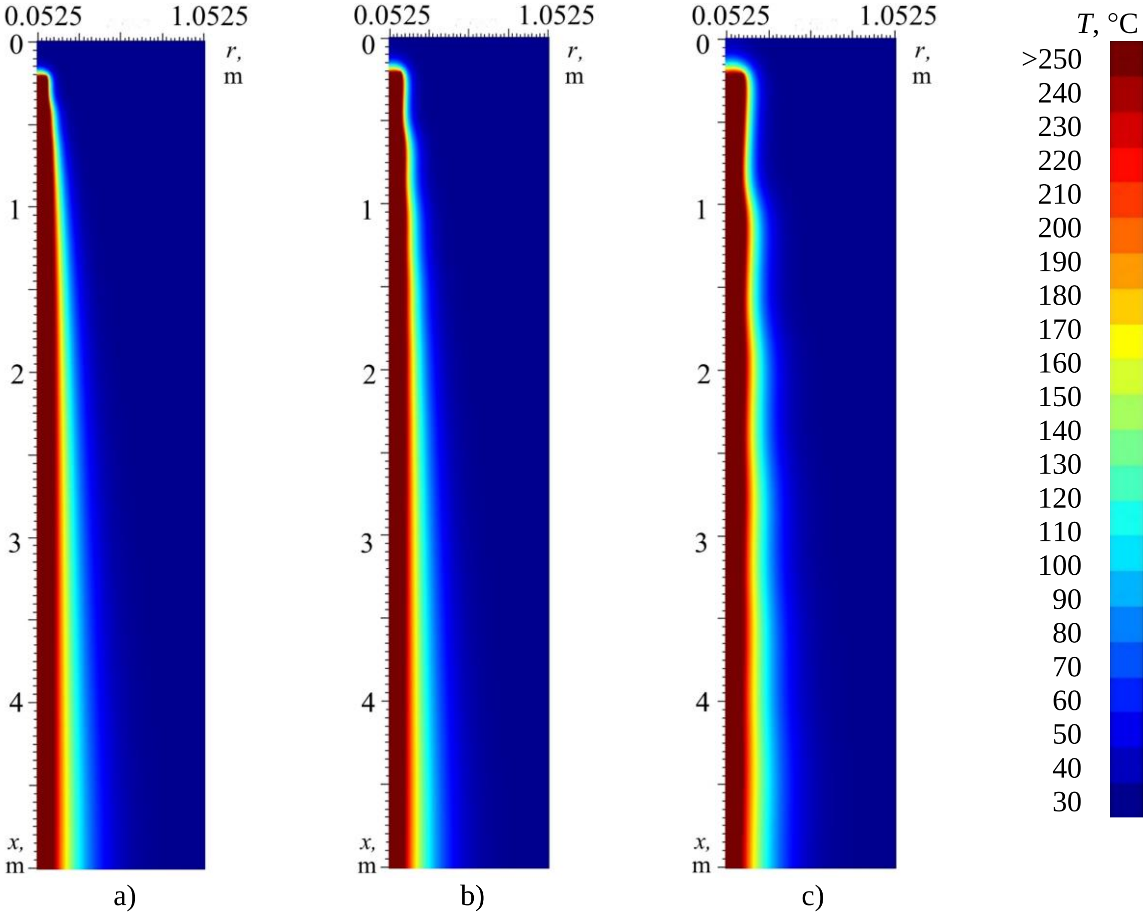

Figure 2. Isotherms in the rock massif during plasma reaming of the borehole. The time of exposure of the plasma-forming gas to the borehole surface $\Delta\tau_p$: a) 600 s; b) 1200 s; c) 2400 s.

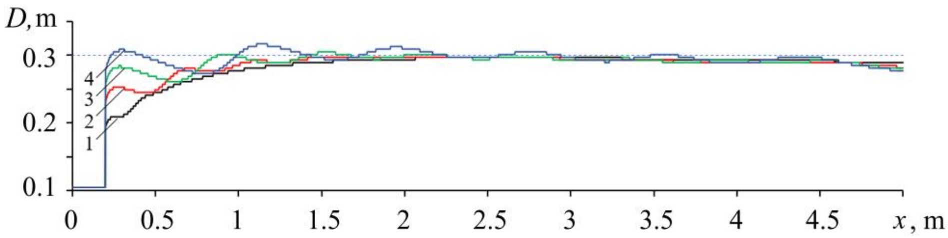

Figure 3. Change of the current diameter of the borehole by depth. The time of exposure $\Delta\tau_p$: 1 – 600 s, 2 – 1200 s, 3 – 1800 s, 4 – 2400 s.

Table 2. Calculated and experimentally determined productivity of the process of plasma reaming of the borehole.

Plasmatron power, kW	Diameter D_k, mm	Speed of reaming, m/h	Productivity, m^3/h		Error, %
	Experiment in mines of the Kryvyi Rih ore basin (Ukraine)			Calculation	
180	390…400	2.1…2.2	0.233	0.190	18.4
150	200…220	4.0…4.3	0.126	0.147	16.7
150	300…330	2.1…2.3	0.130	0.138	5.8
150	360…370	2.0…2.1	0.186	0.140	25.1
150	390…400	1.7…1.8	0.188	0.142	24.5
140	300	1.6…1.7	0.099	0.121	21.5
140	380…400	1.50…1.57	0.157	0.127	19.0

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4. Conclusions

1. The constructed mathematical model of thermal disintegration of rocks during the reaming of boreholes takes into account the compatibility of the thermogas dynamic problem for a high-temperature heat transfer agent and the thermal problem for the rock heated by this heat transfer agent.

2. The constructed mathematical model of thermal disintegration of rocks allows us to determine the rational parameters of the technology of borehole reaming. Relative error of calculation of process productivity does not exceed 26 %.

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