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APPLICATION OF SUPERSONIC GAS JETS FOR ROCK DESTRUCTION

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Abstract. This paper investigates in detail the aspects of supersonic gas jets application in the process of thermal destruction of rocks. The main attention is paid to various aspects of heat transfer, which is key in the use of such methods. The main thermodynamic parameters of a high-intensity gas heat carrier in interaction with rocks are considered. Important characteristics are the heat transfer coefficient from the gas jet to the rock, the effective gas temperature at the rock surface and the specific heat flux. In order to achieve a more accurate mathematical description of the process of thermal destruction of rocks, the authors present a model of the interaction between the gas jet and the rock. They draw attention to the importance of the correct choice of geometric and thermal modeling parameters. Particular attention is paid to the stress-strain state of the rock under the influence of the gas jet heat flow, which is a key aspect in analyzing the efficiency of the fracture process. Various methods and parameters affecting the efficiency of heat exchange between the gas jet and the rock are also analyzed. An elastic half-space, which is a rock interacting with an external high-temperature medium, is considered. Heat exchange occurs according to the law of convection, and the maximum parameters of heat exchange from the jet to the rock are in the vicinity of the central point of its spreading at braking on the rock surface. The stress-strain state of the rock under the influence of the gas jet heat flow is investigated.

Key words: thermal tool, in-chamber pressure, fire-jet destruction, rocks.

Introduction. The study of practical use of high-speed supersonic gas jets in various technological processes of destruction of rocks and other materials, as well as the creation of a new class of thermodynamic tools for gas-flame spraying of metals confirms the relevance of the development of intensive technologies based on supersonic heat flows.

In the process of thermal and combined rock destruction, a high-temperature gas jet moving at high speed is used. A jet burner is usually used as a heat generator. The supersonic gas jet discharged from the nozzle of the jet burner forms a complex structure with compaction jumps and varying cross-section. After the compaction jumps, the static pressure in the jet is compared with the ambient pressure, which leads to the cessation of periodic parameter changes and the beginning of the main jet section.

Materials and methods of research. From a physical point of view, the heat transfer parameters depend on the density of the coolant, its velocity, temperature and the condition of the rock surface. For rocks prone to thermal brittle fracture, the downhole during fire drilling is almost a hemisphere with a smooth surface. The temperature of the coolant primarily depends on the type of fuel used or on the voltage at the electrodes. Thus, the controlled parameters of the gas jet are its density and velocity. The product of density by velocity is called the mass velocity of the jet. This indicator is the most important, as it allows you to control the heat transfer parameters when changing it.

With a change in the thermodynamic parameters of the gas jet along its length, its heat transfer properties also change, which ultimately affects the rate of thermal brittle destruction of rocks. Therefore, the distance from the burner nozzle cutoff to the rock surface must be strictly defined, satisfying the conditions for ensuring the maximum linear rate of destruction and the formation of the bore diameter of wells.

The complexity of the heat transfer process in the presence of chemical reactions and the lack of necessary data on the rate of their flow under thermal drilling conditions do not allow the use of computational and theoretical methods to determine the heat transfer properties of gas jets with sufficient accuracy.

For example, the heat transfer coefficient can be estimated approximately by the formula

$$\alpha = StC_p\rho W_g, \quad (1)$$

As can be seen from formula (1), in order to determine the heat transfer coefficient, experimental data on the velocity, density, and heat capacity of the gas stream at the place where it meets the rock are needed. Determining the indicators is much more difficult than directly measuring the heat transfer parameters of gas jets.

For the experimental evaluation of such parameters of supersonic gas jets as specific heat flux, heat transfer coefficient and effective temperature, special heat receivers with specified thermophysical properties have been developed, allowing to simulate to a certain extent the heat transfer process in relation to the thermal destruction of rocks [2,3].

To mathematically describe the process of brittle thermal destruction of rocks, which occurs during fire drilling of boreholes and wells, well expansion, cutting and processing of rock blocks, it is necessary to choose the right geometric and thermal models, justify the boundary conditions and introduce some assumptions, without which the solution of the problem is impossible today, and if possible, it is so difficult that it is unacceptable for practical use.

The choice of geometric and thermal models must be made as a whole, taking into account the spatial interaction of the rock with the coolant and its heat transfer parameters.

An elastic half-space with rock properties and an external high-temperature medium with a certain temperature distribution law on the heating surface can be used as a process model (Figure 1). The heat exchange of an external high-temperature medium with an elastic half-space occurs according to the law of convection.

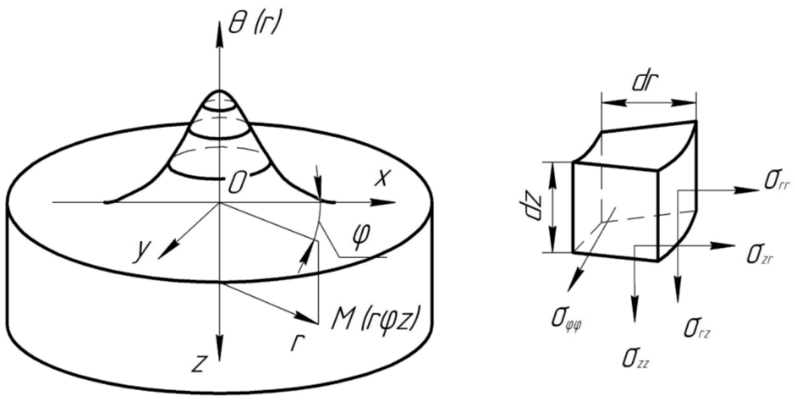

Figure 1 - Thermodynamic model of the coolant–rock system

The assumptions that must be made when describing the process are as follows: the rock is considered as an isotropic and elastic solid; the properties of the rock do not depend on temperature and are assumed to be equal to the average in the range from the initial temperature to the fracture temperature; the high-temperature medium (coolant) is chemically inactive. The fracture temperature is understood as the average thickness temperature of particles separated during thermal drilling [2,3].

For the accepted model, taking into account the stated assumptions, the equations describing displacement and stress state are known [5] and have the form:

$$\left.\begin{aligned}\frac{\partial\sigma_{xx}}{\partial x}+\frac{\partial\sigma_{xy}}{\partial y}+\frac{\partial\sigma_{xz}}{\partial z}=\rho\frac{\partial^2U_x}{\partial r^2};\\ \frac{\partial\sigma_{xy}}{\partial x}+\frac{\partial\sigma_{yy}}{\partial y}+\frac{\partial\sigma_{yz}}{\partial z}=\rho\frac{\partial^2U_y}{\partial r^2};\\ \frac{\partial\sigma_{zx}}{\partial x}+\frac{\partial\sigma_{zy}}{\partial y}+\frac{\partial\sigma_{zz}}{\partial z}=\rho\frac{\partial^2U_z}{\partial r^2};\end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned}\sigma_{xx}=2G\left[\tfrac{\mu}{1-2\mu}l+\varepsilon_{xx}-\tfrac{1+\mu}{1-\mu}\beta(T-T_0)\right];\\ \sigma_{yy}=2G\left[\tfrac{\mu}{1-2\mu}l+\varepsilon_{yy}-\tfrac{1+\mu}{1-\mu}\beta(T-T_0)\right];\\ \sigma_{zz}=2G\left[\tfrac{\mu}{1-2\mu}l+\varepsilon_{zz}-\tfrac{1+\mu}{1-\mu}\beta(T-T_0)\right];\\ \sigma_{xy}=2G\varepsilon_{xy};\ \sigma_{xz}=2G\varepsilon_{xz};\ \sigma_{yz}=2G\varepsilon_{yz},\end{aligned}\right\} \qquad (3)$$

where ρ is density; U_x, U_y, U_z are displacements along the x, y, z axes; G is the shear modulus; μ is the Poisson's ratio; $l=\varepsilon_{xx}-\varepsilon_{yy}+\varepsilon_{zz}$are volumetric deformations; ε_{ik} are deformations along the corresponding axes;

$$\left.\begin{aligned}\varepsilon_{xx}=\frac{\partial U_x}{\partial x};\ \varepsilon_{yy}=\frac{\partial U_y}{\partial y};\ \varepsilon_{zz}=\frac{\partial U_z}{\partial z};\\ \varepsilon_{xy}=\frac{1}{2}\left(\frac{\partial U_x}{\partial y}+\frac{\partial U_y}{\partial x}\right);\ \varepsilon_{xz}=\frac{1}{2}\left(\frac{\partial U_x}{\partial z}+\frac{\partial U_z}{\partial x}\right);\\ \varepsilon_{yz}=\frac{1}{2}\left(\frac{\partial U_y}{\partial z}+\frac{\partial U_z}{\partial y}\right),\end{aligned}\right\} \qquad (4)$$

where β is the coefficient of linear thermal expansion; T_0 and T are the initial and current temperatures of the elastic half-space.

The determination of the current temperature of the half-space is reduced to solving a differential equation of thermal conductivity of the form.

$$\frac{\partial T}{\partial r}=a\nabla^2T, \qquad (5)$$

where a is the thermal conductivity of the rock; ∇^2 is the Laplace operator;

$$\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2} \qquad (6)$$

The system of equations (2) is a dynamic problem that takes into account movements in the rock, taking into account the propagation of elastic waves under boundary conditions of the first kind, taking into account dynamic components is mandatory.

As the results of measurements of the parameters of high-speed gas jets of thermowells [3,4] have shown, the temperature in the coolant spreading spot is distributed according to the Gauss error law and can be described by the dependence

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$$\theta = \theta_0 exp\left(-\frac{r^2}{4\delta}\right), \qquad (7)$$

where θ_o is the temperature in the center of the spreading spot; r is the distance from the center of the spreading spot; δ is the parameter of the temperature distribution curve.

In relation to the processes of thermal and combined destruction of rocks, heat carriers can be very diverse: chemical fuel combustion products, plasma, air, steam, steam-gas mixtures, etc.

Heat transfer from the coolant to the rock can be carried out by radiation or convection. For the most part, heat transfer during thermal destruction of rocks is carried out by convection through a certain boundary layer between the coolant and the rock.

The amount of heat transferred by the coolant to the rock depends on many factors, the main of which are: temperature pressure (the difference between the temperature of the coolant and the rock), the speed and nature of the movement of the coolant at the rock surface, the nature of the heated surface, the thermophysical properties of the coolant and the rock, and a number of others.

Convective heat transfer between the coolant flow and the rock surface is called heat transfer by convection or contact.

The specific heat flux entering the rock during convective heat exchange is determined by the expression

$$q = \alpha(T_т - T_п), \qquad (8)$$

where α is the coefficient of convective heat transfer; $(T_т - T_п)$ is the difference between the temperature of the coolant and the surface of the rock.

When exposed to a gaseous or liquid coolant on a rock near its surface, the coolant velocity drops from maximum to zero. The thin layer of the coolant inside which this is carried out is called the dynamic boundary layer δ. The thickness of this layer depends on the dynamic viscosity μ of the coolant and increases with its growth [5,6].

The temperature in the boundary layer varies from the temperature of the rock $T_п$ to the temperature of the coolant $T_т$. The thickness within which the specified temperature change occurs is called the thermal boundary layer, which for gases and water is equal to the thickness of the dynamic layer.

Since the velocity of the coolant in the boundary layer decreases to zero, it can be assumed that heat transfer to the rock is carried out according to the law of thermal conductivity, i.e.

$$q = -\lambda_T \frac{\partial T}{\partial n}, \qquad (11)$$

where λ_T is the thermal conductivity of the coolant.

The magnitude of the temperature gradient in the boundary layer can be expressed as

$$\frac{\partial T}{\partial n} = \frac{T_т - T_п}{\delta_b} \qquad (12)$$

Then, taking into account (12), the heat flow entering the rock will be

$$q = -\frac{\lambda_T}{\delta_b}(T_т - T_п) \quad (13)$$

From the comparison (8) and (13) it can be seen that the coefficient of convective heat exchange

$$\alpha = \frac{\lambda_T}{\delta_b} \quad (14)$$

Since λ_T is greater for liquids than for gases, it should be expected that the use of liquid coolants for the purpose of thermal destruction of rocks will be more effective than the use of gaseous coolants (provided all other parameters are equal). However, in most cases, a high-velocity gas stream is used as a coolant [7,8].

The process of interaction of a high-intensity gas coolant with rocks takes place in almost all cases associated with their thermally directed brittle destruction.

Most often, a supersonic high-temperature jet generated by jet burners acts as a coolant, which is formed as a result of the release of combustion products from the combustion chamber through the nozzle. Near the surface of the rock, the flow is inhibited, while a surge of compaction takes place.

The density of the flow and its temperature increase sharply in the surge of compaction. After the seal jump, the flow velocity becomes subsonic.

Along the axis of the jet, at the point where it meets the rock, the flow is completely inhibited, and in the vicinity of this point, a partial deceleration of the flow and the formation of a boundary layer are observed. In the center, the thickness of the boundary layer is zero, and as you move away from it, the thickness of the layer increases and the flow in it passes from laminar to turbulent.

Since the intensity of heat transfer depends on the mass velocity pW of the coolant, the maximum heat transfer parameters from the jet to the rock will be in the vicinity of the central point of the spreading spot of the jet when it decelerates on the rock surface. As you move away from the center, the thickness of the boundary layer increases, which is an additional resistance that prevents heat transfer of the coolant with the rock. In this regard, the heat transfer parameters of the coolant will decrease.

The results of the study. The main thermodynamic parameters of a high-intensity gas coolant when braking it against the surface of a destructible rock are: the coefficient of heat transfer from the jet to the rock α, the effective temperature of the coolant in the immediate vicinity of the surface of the T_e rock and the specific heat flux q.

The second type of heat transfer when using supersonic high-temperature gas jets as a coolant is radiation. Thermal radiation is the transfer of energy by electromagnetic waves from more heated bodies to less heated ones, even if there is a vacuum between them. Thus, the intensity of heat exchange by radiation depends on the temperature difference between the coolant and the rock, as well as on the ability of the latter to absorb electromagnetic waves.

The radiant energy incident on a rock, depending on its electromagnetic properties, shape and surface condition, is partly absorbed and converted into heat, and partly passes through it or is reflected. Bodies that have the ability to completely absorb radiant energy are called completely black. There are no such bodies in the nature of notes, and real rocks absorb only part of the energy in relation to an absolutely black body:

$$E = E_0\varepsilon, \quad (15)$$

where E is the radiating (or radiating) ability of a rock; E_0 is the radiating ability of a completely black body; ε is the degree of blackness of the rock (for most minerals ε = 0,5÷0,9).

The radiation absorption capacity of a rock, depending on the temperature difference between it and the ΔT source, can be determined from the Stefan–Boltzmann equation

$$E = \varepsilon C_0 \left(\frac{\Delta T}{100}\right)^4, \tag{16}$$

where C_0 *is* the emission coefficient of a completely black body.

If the heat carrier is a gas, then the specific heat flux entering the rock due to radiation absorption is determined by the formula

$$q_l = \varepsilon_{pr} C_0 \left(\frac{\Delta T}{100}\right)^4, \tag{17}$$

where $\varepsilon_{pr} = \varepsilon' \varepsilon_{ch}$; $\varepsilon' = \frac{\varepsilon+1}{2}$; ε_{ch} is the degree of blackness of the gas

In practice, the formula is used

$$q_l = \alpha_l \Delta T, \tag{18}$$

where α_l s the heat transfer coefficient by radiation.

It follows from (17) and (18):

$$\alpha_l = \frac{\varepsilon_{pr} C_0 \Delta T^3}{100^4} \tag{19}$$

The amount of heat entering the rock due to radiation absorption from a high-temperature gas jet of thermal tools, for example during fire drilling, is more than an order of magnitude lower than due to convective heat transfer. This is primarily due to the low value of the degree of blackness of the gas jet and the relatively small value of its temperature.

The heat transfer parameters of a high-temperature gas jet depend on the angle of its encounter with the rock. With an orthogonal meeting in the central part of the spreading spot, the heat transfer parameters are maximal and decrease sharply as they move away from the center. When the jet meets the rock at an angle (all other things being equal), the heat transfer parameters in the central part of the spreading spot will be lower, and their rate of decrease with distance from the center is lower than with an orthogonal meeting [9].

The criterion for choosing the optimal angle of encounter of the jet with the rock during its cutting and processing is the total amount of heat entering the heated surface per unit of time.

Conclusion. Analyzes the features of heat transfer using supersonic gas jets in the context of thermal destruction of rocks. It also examines in detail the main thermodynamic parameters of the high-speed gas flow that play a key role in this process.

As part of the study, a model has been presented and described that allows the computational parameters of the thermal flow-rock interaction to be carried out. This model represents an important tool for analyzing and optimizing the rock fracture process using supersonic gas jets.

Additionally, the paper examines the stress-strain state of the rock under the influence of the heat flux. This provides insight into how rocks respond to high velocity gas jets, which is essential in the planning and execution of rock fracture operations in mining and other fields.

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ТАУ ЖЫНЫСТАРЫН БҰЗУ ҮШІН ДЫБЫСТАН ЖОҒАРЫ ГАЗ АҒЫНДАРЫН ҚОЛДАНУ

Аңдатпа. Бұл мақалада тау жыныстарының термиялық ыдырау процесінде дыбыстан жоғары газ ағындарын қолдану аспектілері егжей-тегжейлі қарастырылады. Мұндай әдістерді қолдану кезінде маңызды болып табылатын жылу алмасудың әртүрлі аспектілеріне назар аударылады. Тау жыныстарымен өзара әрекеттесу кезінде жоғары қарқынды газ салқындатқышының негізгі термодинамикалық параметрлері қарастырылады. Маңызды сипаттамалар-газ ағынынан жыныsқа жылу беру коэффициенті, жыныс бетіне жақын газдың тиімді температурасы және меншікті жылу ағыны. Тау жыныстарының термиялық ыдырау процесінің дәл математикалық сипаттамасына қол жеткізу үшін авторлар газ ағынының тау жыныстарымен өзара әрекеттесу моделін ұсынады. Модельдеудің геометриялық және жылу параметрлерін дұрыс таңдаудың маңыздылығына назар аударылған. Газ ағынының жылу ағынының әсерінен тау жыныстарының кернеулі деформацияланған күйіне ерекше назар аударылады, бұл бұзылу процесінің тиімділігін талдаудың негізгі аспектісі болып табылады. Газ ағыны мен тау жыныстары арасындағы жылу алмасу тиімділігіне әсер ететін әртүрлі әдістер мен параметрлер де талданады. Сыртқы жоғары температуралы ортамен әрекеттесетін тау жынысы болып табылатын серпімді жартылай кеңістік қарастырылады. Жылу алмасу конвекция заңына сәйкес жүреді, ал ағыннан жынысқа жылу алмасудың

максималды параметрлері жыныс бетінде тежеу кезінде оның таралуының орталық нүктесінің маңында болады. Газ ағынының жылу ағынының әсерінен жыныстың кернеулі деформацияланған күйі зерттелді.

Кілт сөздер: жылу құралы, ішкі қысым, отқа төзімді бұзылу, тау жыныстары.

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ПРИМЕНЕНИЕ СВЕРХЗВУКОВЫХ ГАЗОВЫХ СТРУЙ ДЛЯ РАЗРУШЕНИЯ ГОРНЫХ ПОРОД

Аннотация. В данной статье подробно исследуются аспекты применения сверхзвуковых газовых струй в процессе термического разрушения горных пород. Основное внимание уделяется различным аспектам теплообмена, который является ключевым при использовании подобных методов. Рассматриваются основные термодинамические параметры высокоинтенсивного газового теплоносителя при взаимодействии с горными породами. Важными характеристиками являются коэффициент теплоотдачи от газовой струи к породе, эффективная температура газа у поверхности породы и удельный тепловой поток. Для достижения более точного математического описания процесса термического разрушения горных пород авторы представляют модель взаимодействия газовой струи с породой. Обращают внимание на важность правильного выбора геометрических и тепловых параметров моделирования. Особое внимание уделяется напряженно-деформированному состоянию породы под воздействием теплового потока газовой струи, что является ключевым аспектом при анализе эффективности процесса разрушения. Анализируются также различные методы и параметры, влияющие на эффективность теплообмена между газовой струей и горной породой. Рассматривается упругое полупространство, представляющее собой горную породу, взаимодействующую с внешней высокотемпературной средой. Теплообмен происходит по закону конвекции, а максимальные параметры теплообмена от струи к породе находятся в окрестности центральной точки ее растекания при торможении на поверхности породы. Исследовано напряженно-деформированное состояние породы под воздействием теплового потока газовой струи.

Ключевые слова: термоинструмент, внутрикамерное давление, огнеструйное разрушение, горные породы.