Blasthole jet drilling parameters evaluation by test rig

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Abstract. The jet drilling method has significant advantages over mechanical ones. The article presents the results of the theoretical and experimental jet drilling apparatus for drilling blast holes in hard rocks granite and gneiss studies using the developed test rig. The main difference between the studied device and traditional thermal spallation drills is the low temperature of the working fluid. The specific energy consumption method was proposed to evaluate parameters of the jet drilling apparatus for various rocks types. It has been shown that minimal specific energy consumption for hard rocks is obtained with minimal chamber pressure sufficient for reaching certain Mach number at the nozzle exit. The developed test rig has experimentally shown a stable drilling process and, at the same time, a long durability of the apparatus.

1. Introduction

Drilling and blasting are the first in the chain of technological processes of mining and largely determine the cost of mining. In large quarries, the costs of drilling and blasting operations reach 30% of the total production costs [1].

The most common method for drilling blast holes today is the mechanical method: rotary drilling, carried out by cone bits, and rotary hammer drilling, carried out by pneumatic hammers. Among other drilling methods, we pick out the method of thermal spallation drilling by means of high-temperature thermal exposure to the rock with the jets of combustion products of kerosene and oxygen or air [2,3].

The specific energy absorption of the rock during mechanical drilling is a function of the compressive strength of the rock. At the same time, the specific energy absorption of the rock by thermal spallation drilling depends on the tensile strength of the rock, since in this method the rock is destroyed due to the separation of small particles from the surface layer due to tensile stresses in the highly heated material. Values of tensile strength for rocks are much lower than the compressive strength of the same rocks. Therefore, from the point of view of the magnitude of the specific energy that must be introduced into such rocks for their destruction, the thermal spallation method of drilling turns out to be more advantageous in comparison with the mechanical one [4].

The advantage of the thermal spallation drilling method over the mechanical one is also the absence of direct contact of the drilling tool (burner) with the rock, which, theoretically, should ensure the absence of tool wear, so much characteristic of the mechanical method. However, the classical
thermal spallation method of drilling uses gas jets of extremely high temperature, which is 1600-2800 °C. At such temperatures, the drilling tool has an extremely low durability.

It is known that hard rocks begin to break at temperatures not exceeding 600 °C [5,6]. If someone organizes a gas jet with a low, but sufficient temperature for rock destruction, then one can ensure long-term durability of the drilling tool. At a low temperature, other parameters of the jet will also have a significant impact on the rock destruction process, for example: jet velocity, angle of the jet impact, pressure exerted by the jet on the rock. A drilling method in which the rock is destroyed due to the combined thermal and gas-dynamic effects of the working fluid jets can be called “jet” drilling, a device that implements such principle - jet drilling apparatus (JDA).

2. Methods and Apparatus

The temperature range of the working fluid for the destruction of hard rocks can be determined as follows. The lower limit of the temperature range of the working fluid is defined as the temperature of the destruction of the rock:

\[ T_D = \frac{2\sigma_C(1-\mu)}{\beta \cdot E}, \]

where \( \sigma_C \) is the ultimate compressive strength; \( \mu \) is the Poisson's ratio; \( \beta \) is the coefficient of thermal expansion; \( E \) is Young's modulus.

The upper value of the working fluid temperature range is determined by the lowest temperature of the following: the characteristic thermal effects in the rock material \( T_{\text{eff}} \) [7] (melting, dissociation, dehydration, etc.) and the maximum temperature of the long-term thermal strength of the construction material of the apparatus \( T_{\text{max, dur}} \). It is desirable that the construction of the apparatus is made of common structural materials.

Typical values for the temperature range are shown in table 1.

| Type of rock    | \( T_D \), °C | \( T_{\text{eff}} \), °C | Construction material | \( T_{\text{max, dur}} \), °C |
|-----------------|---------------|-----------------|-----------------------|------------------|
| Quartzite       | 250 – 350     | 1400            | AISI 321              | 800              |
| Granite, gneiss | 350 – 600     | 1400            | AISI 310S             | 1000             |

To obtain a high-temperature working fluid in traditional thermal spallation drilling tools two components are used: fuel - liquid hydrocarbon fuels such as kerosene or diesel fuel; oxidizer - gaseous oxygen or air.

In JDA, to obtain a working fluid with the required temperature, which is significantly lower than the temperature of the products of complete combustion of kerosene with air or oxygen, it is proposed to use a three-component steam and gas generator (SGG). SGG (figure 1) is based on a small-sized combustion chamber of a liquid propellant rocket engine, which implements the injection of refrigerant (water or air) passing through the cooling jacket of the combustion chamber 2 through a series of openings 4 into the stream of high-temperature combustion products. The interaction of the refrigerant with the products of combustion in the evaporation part 3 allows getting at the outlet a working fluid with the required temperature. The evaporation part of the combustion chamber has a thread at the end for connection with a replaceable nozzle head. Further, the jets of the working fluid flowing through the nozzle drill head interacts with the rock. The design of SGG is patented.

SGG is designed to obtain the following range of parameters of working fluid (table 2).

| Parameter     | Value range |
|---------------|-------------|
| Chamber pressure, MPa | 1 – 20 |
| Parameter                          | Specification       |
|-----------------------------------|---------------------|
| Mass flow rate of working fluid   | 0.6 – 1.3 kg/s      |
| Temperature of working fluid      | 500 – 800 °C        |

Figure 1. The design of SGG: 1 – firing device; 2 – combustion chamber; 3 – evaporation part of combustion chamber; 4 – openings for refrigerant injection; 5 – openings for refrigerant injection into surrounding area (optional).

The drilling scheme using JDA is shown in figure 2.

Figure 2. The drilling scheme using JDA: 1 – SGG; 2 - nozzle head; 3 – dome; 4 – sealing.
The JDA, which consists of SGG 1 and the nozzle head 2, is centered and compacted in the dome 3 using the sealing 4. The sludge and exhaust gas generated during drilling through the outlet on the dome move into the sludge removal system consisting of an adsorbing cyclone, a filter and a heat exchanger for heat recovery. The small drilling depth, typical for the blasthole, allows one to drill each hole in one operation without additional installation and docking operations. This allows the use of standard flexible hoses for supplying components, which greatly simplifies the JDA component supply and control system, and reduces the total time required for drilling and tying the well.

The JDA nozzle head with installed nozzles is the main working body in jet drilling. The working fluid flows out through them at supersonic speed. The effectiveness of JDA and its nozzle head largely determines the effectiveness of jet drilling method in general. To determine the optimal ranges of the parameters of the working fluid jets for various types of rocks, an analytical method was proposed that allows the selection of design and operational parameters of the JDA at the early stages of design. The algorithm is implemented as the program code in the Matlab environment. Since the existing energy criteria do not reflect the features of jet drilling, the specific energy consumption of drilling 1 m$^3$ of rock by the jet drilling method is proposed:

$$E_J = \frac{m^*_F \cdot H_u}{V} \left[ \text{J/m}^3 \right].$$

(2)

where $V$ is average volumetric rate of rock drilling, m$^3$/s; $m^*_F$ is mass flow rate of fuel in JDA, kg/s; $H_u$ is lower net calorific value of fuel, J/kg. This criterion also allows determining the average energy consumption for drilling 1 m for a well of a given diameter.

To study the drilling process using JDA, an experimental bench was designed and manufactured. It provides the supply of components to the JDA (kerosene, compressed air, water), the displacement of the JDA relative to the rock sample and the evaluation of the average drilling speed.

3. Results and Discussions

The results of the calculation analysis according to the developed methodology are the basis for choosing the design and operational parameters of the JDA: chamber pressure; refrigerant excess ratio; Mach number of the flow at the nozzle exit; half-angle of the nozzle.

For the calculation analysis, the following components were selected: oxidizer - air; fuel - kerosene with the following characteristics: carbon content by weight - 85.9%, hydrogen - 14.1%. Refrigerant is water, air. For the calculation, the pressure range in the JDA from 1 to 15 MPa was selected.

Some significant results of calculations at a working fluid temperature of 650 °C for granite using various refrigerants are shown in figures 3-6. The graphical dependencies below show that the specific energy consumption of jet drilling using air refrigerant is lower compared to water refrigerant. It can be explained by a change in the parameters of the jet due to a change in the specific heat capacities ratio of the working fluid due to its greater ballasting with air to reach the same temperature. It is also noticeable that if chamber pressure increases, the specific energy consumption of jet drilling also increases, which can be explained by an increase in the resistance of the medium near the nozzle head. An increase in the nozzle half-angle at the same values of the Mach numbers and chamber pressure leads to a certain decrease in the minimum energy consumption of jet drilling, obviously due to an increase in the width of the jet and the contact area of the jet with the rock surface. It is common practice to use conical nozzle half-angle value up to 15°, so it is recommended to choose the value for about 15° for JDA.

As a result of bench experiments, a stable process of drilling of rocks (granites and gneisses) with an average speed of up to 2.5 mm/s was obtained. Field tests showed that this method of drilling could also be applied to more soft types of rocks; however, it requires the use of nozzle heads of a different design.
Figure 3. Dependence of the specific energy consumption of jet drilling on the chamber pressure at various Mach numbers at the nozzle exit; the half-angle of the nozzle is 10°, refrigerant is water.

Figure 4. Dependence of the specific energy consumption of jet drilling on the chamber pressure at various Mach numbers at the nozzle exit; the half-angle of the nozzle is 10°, refrigerant is air.
4. Conclusion

Experimental studies have shown that when using JDA with a low temperature of the working fluid, a stable process of drilling hard rocks with an average speed of up to 2.5 mm/s could be obtained. This method is also applicable for drilling wells in rocks of lower strength by modifying the nozzle head.
It is worth noting that the jet drilling method has a number of significant advantages for the blasthole drilling compared to thermal spallation and mechanical drilling methods:

− the jet drilling method provides the destruction of rock with minimal energy absorption;
− JDA has a long durability since it does not have moving parts, does not contact the rock during operation and has the ability to select the appropriate parameters of the working fluid, providing long-term durability of structural elements;
− the drilling machine with JDA does not require a heavy foundation, it is mobile and does not require preparation of the drilling site, which allows it to be used in hard-to-reach places and extreme conditions;
− due to the exclusion of some mounting and docking operations and the high reliability of the design, the JDA has a high coefficient of technical use;
− widespread components such as air, water and kerosene or diesel fuel are used as fuel components.

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