Optimum Cooling Conditions of Rocks in Underground Facilities of Cryolithic Zone

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Abstract
The estimation of the energy efficiency of selecting the optimum ventilation conditions of mine workings with variable air flow rate during the winter period was performed. As an efficiency criterion the degree of energy costs reduction when facility ventilating with variable and constant air flow was used. In a specific example it was shown that a simple change in the air volume during the winter period allows you to halve the energy costs required to maintain the frozen state of the rock masses and ensure the stability of the mine workings of the underground facilities.
Key words: UNDERGROUND FACILITY, ROCKS RIGIDITY, THERMAL CONDITIONS, ENERGY EFFICIENCY, CRYOLITHIC ZONE

For underground facilities located in frozen rocks, one of the important tasks is to maintain rigidity of the mine workings. In many cases this can be achieved while preserving rocks at frozen state throughout their lifetime [1, 2, 3, 4, 5]. Moreover, studies have shown [6] that the additional cooling of rocks leads to increase of the mine workings rigidity. As we have previously shown the selection of the rocks cooling conditions of the underground facilities has a significant impact on the overall energy costs for creating the standard operating conditions [7]. Thus, the need to develop a special technique, which would allow when designing the underground facilities of the cryolithic zone selecting the optimal mode of workings ventilation as a factor for the rocks rigidity as well as a factor of economy of power resources becomes evident. The task was formulated as follows. You need to select the optimal distribution of the air flow rate during the winter period, which would satisfy the given criterion of quality, and energy consumption for ventilation facility would be minimal. Natural limitations are: the upper limit - the fan discharge, the lower – the set level of air exchange in the facility according to sanitary norms. As a criterion of quality the temperature rocks wall is selected at a predetermined distance along the length of the mine working. The mathematical problem is reduced to the following optimization problem $\sum_{i=1}^{KOL} G_i \to \min$ when limitations $G_{\min} \le G_i \le G_{\max}$, $i = \overline{1, KOL}$, $T^* = T_{cr}$, where G_i – air flow rate in *i*-th winter month, m^3/s; KOL – a number of winter months; T^* – working wall temperature at the predetermined summer time at a given distance from the entrance of working,°C; T_{cr} – the critical temperature for the mine working wall (quality criterion), °C, G_{min} – minimal winter air flow rate, м^3/s; G_{max} – maximal winter air flow rate, m^3/s.

The general algorithm for solving the problem is reduced to the following. First the winter months are arranged by the following rules:

$$1) \ldots T_1 \le T_2 \le \ldots \le T_N,$$

2) $...T_{1,2,...N} \geq T_{2,3,...N} \geq ... \geq T_{N-1,N} \geq T_N$, $N \leq KOL$

where T_i – temperature T^*, where in i –th winter month from the array the air flow rate is equal to G_0,and in others it equals minimal value; $T_{i1,.....,i2}$ – temperature T, when i,....,$i2$ months have equal air flow rate the amount of which is equal to G_0, and the rest – minimal; G_0 – any value of air flow rate, $G_{min} \leq G_0 \leq G_{max}$.

Further, the initial problem is divided into one-dimensional optimization problems solved by using the following algorithm:

Step 1. The solution of the problem:

$$T^*(G) \rightarrow T_{cr}$$
$$G = G_1 = G_2 = ... = G_N,$$
$$G_{min} \leq G_i \leq G_{max}, \quad i = \overline{1, N}.$$

The result of solving this problem is denoted by G^0, and sum $\sum_{i=1}^{N} G_1$ – by SUM. If the problem has no solution, then go to step 6.

Step 2. $i = 1$, $G_1^0 = G^0$.

Step 3. Solution of the search problem $G_{i\ min}$ when limitations:

$$G_{i+1} = G_{i+2} = ... = G_N,$$
$$\sum_{j=i+1}^{N} G_j \leq SUM$$
$$G_{min} \leq G_i \leq G_i^0$$

The result of solving this problem is denoted by G_i^{opt}. If there is no solution we go to step 5.

Step 4. The solution of the problem:

$T^*(G) \rightarrow T_{cr}$ when limitations:

$$G = G_{i+1} = G_{i+2} = ... = G_N,$$
$$G_0 \leq G_j \leq \frac{G_0 - G_i^{opt}}{N - i}, \quad j = \overline{i+1, N}$$

The result of solving this problem is denoted by G^0_{i+1}.

Step 5. i=i+1. If $i \leq N$-1,we go to the step 4.

Step 6. The end of the algorithm.

The result of whole algorithm is a sequence of optimal values of air flow rates for the winter months:

$$G_1^{opt}, G_2^{opt}, ..., G_n^{opt}.$$

Due to the fact that the main parameter used in the program - the temperature of the mine workings wall is not clearly expressed, and determined from the solution of the corresponding model problem [6, 7], for solving one-dimensional optimization problems used in described algorithm, the method of golden section is selected, which does not require the calculation of derivatives of the objective function.

As an example, let us consider the selection of optimal ventilation mode of underground facility 1800 m in length and cross section of 10 m², located in the frozen ground with a temperature of -5°C. The maximal possible air flow rate by the fan discharge is 15 m³/s, minimal on sanitary norms is 5 m³/s in winter period and 6.5 m³/s in summer. Ventilation starts from September. The annual cycle is considered.

Analysis of these calculations for the test case shows that supply of the maximal amount of air in winter does not lead to efficiency increase and does not improve the quality criterion for which in this case, accepted the surface temperature of the rocks (T ≤ 0°C) at the distance of 1.800 m from the start of mine working. This may be, for example, temperature of the rock at the end of heat exchange workings network or the outlet temperature of the underground cold-storage plant. The graphs (Fig.1) show a change of surface temperature of the mine working at the end of underground facility with length of 1800 m.

As can be seen from the graphs, in winter period the supply of maximal amount of air, which provides the necessary level of air exchange in the facility, does not lead to achievement of the objective, i.e. maintaining the rocks temperature below the melting point of ice, and since the second half of July the rock temperature rises above zero degrees Celsius (curve 2). During the winter period supply of the amount of air with maximal possible discharge of the fan in order to freeze the rocks gives the desired effect (curve 1). However, energy costs in this case increase sharply. Adjusting the amount of air by the developed algorithm also leads to the achievement of the objective and performance of the quality criterion (curve 3), but this requires significantly less total amount of air. Let us compare two cases the criterion of quality performance: when maximal and optimal air flow rate.

If in the first case the conditional total air flow rate during the winter period cycle (from October to May) is 105 m³/s, and in the second case is just 70 m³/s, i.e. almost 1.5 times lower. The amount of energy spent on facility ventilation can be calculated using the formula:

$$N = \sum_{i=1}^{n} K G_i^3 \tau_i, \text{ kW} \quad (1)$$

where K – coefficient characterizing the conditions of workings ventilation, kW·s³/(m⁹·h); τ_i – duration of ventilation per month, h; G_i – air flow rate, m³/s; n –amount of winter months, equals seven.

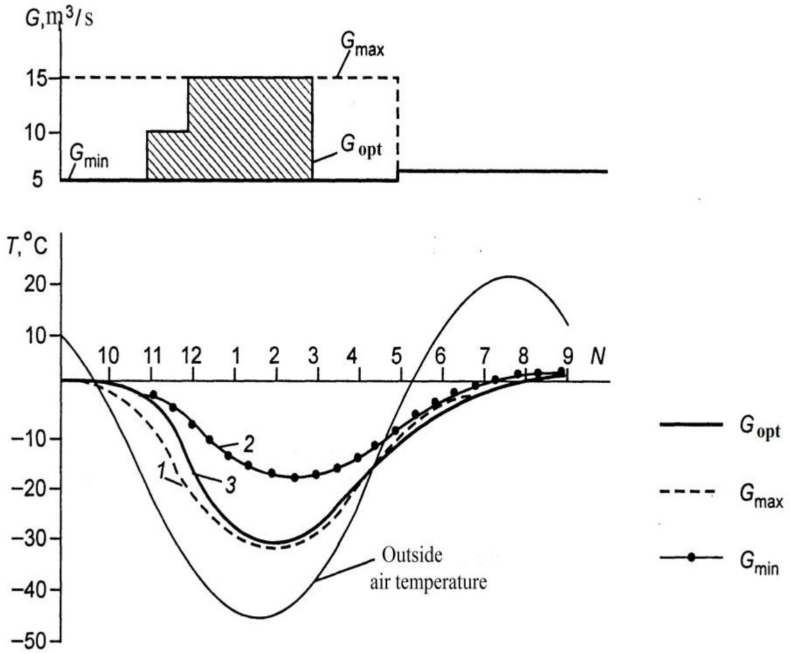

Figure 1. Changing the wall temperature at the end of mine working at different air flow rates in winter period. *1* – when maximal – 15 m³/s; *2* – when minimal – 5 m³/s; *3* –when optimal

Coefficient of reducing energy costs, taking into account the same conditions and duration of ventilation calculated by the formula:

$$f_э = \left(\sum_{i=1}^{n} G^3{}_{max}\,\tau_i\right) / \left(\sum_{i=1}^{n} G^3{}_{opt}\,\tau_i\right) \qquad (2)$$

In this particular case, the coefficient may be determined by the following formula:

$$f_э = 7 \cdot G^3{}_{max} / \left[3G^3{}_{max} + 3G^3{}_{min} + \left(G_{max} - G_{min}\right)^3\right] \quad (3)$$

In quantitative terms, for the above example, the ratio of reducing energy costs is equal to 2.05. That is, the air flow rate regulation without compromising quality criterion allows us to reduce energy costs twofold.

The analysis allows us to draw a conclusion about the expediency when designing underground facilities to carry out a preliminary efficiency assessment of the rocks cooling by the proposed method.

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