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Efficiency evaluation of thermal insulation use in cryolithic zone mine openings

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Abstract
The efficiency of thermal insulation use in underground openings of cryolithic zone was evaluated. The measure of heat flow rate reduction from air to rocks was used as efficiency criterion. Influence of heat-insulating and heat-retaining coatings of the mine openings on rocks temperature conditions formation was analyzed. The conclusion on necessity of development of new combined coatings consisting of heat-insulating and heat-retaining layers was drawn.
Key words: MINE OPENING, THERMAL INSULATION, THERMAL CONDITIONS, ENERGY EFFICIENCY, CRYOLITHIC ZONE

Thermal insulation in the openings of mines and pits is usually used for reduction of energy expenditure for mine air conditioning [1]. In the cryolithic zone mine openings (driven in frozen rocks), thermal insulation must additionally ensure the quality of rocks in frozen condition or minimize depth of thawing of rocks surrounding the opening [2, 3].

Efficiency of thermal insulation use in mine openings can be estimated from the energy standpoint by the measure of heat flow rate reduction in time. Let us consider the simulated mine opening. The dimensionless thermal flow in the opening wall from air to rocks can be calculated at constant temperature in the opening by approximate formula [4]

$$Ki = \frac{Bi}{1 + Bi \ln \delta} \quad (1)$$

where $\delta = f(Fo)$, particularly

$$\delta = 1 + 2\sqrt{Fo}. \quad (2)$$

In formulas (1) and (2), the common notations are accepted: *Fo* – Fourier criterion; *Bi* – Biot number; *Ki* – Kirpichev criterion.

In the limit case of thermal insulation absence, it can be considered that $Bi \to \infty$ therefore, when revealing of uncertainty by L'Hospital rule, we obtain

$$Ki = 1/\ln \delta \quad (3)$$

If there is thermal insulation, the formula (1) is correct; and in this case, the heat-transfer coefficient is equivalent to reciprocal of thermal resistance of heat-protecting layer in *Bi* number.

$$\alpha = \left(\delta_{IN} / \lambda_{IN}\right)^{-1} \text{ W/m}^2 \cdot \text{K} \quad (4)$$

In comparison with non-heat-insulated opening, the measure of heat flow rate reduction in time in heat-insulated opening can be determined by formula

$$\frac{Ki}{Ki^{IN}} = \frac{1 + Bi \ln \delta}{Bi \ln \delta} = 1 + \frac{1}{Bi \ln \delta}. \quad (5)$$

The numerical calculations for this formula are presented in the form of diagrams in Figure. Thus, we used characteristic for rocks, and at the same time very "convenient", initial data, which allow us to pass quickly from dimensionless criteria *Fo* and *Bi* to the dimensional parameters of time and thermal resistance. Such data are the following:

$a = 4{,}56 \cdot 10^{-3}$ m²/h; $R_0 = 2$ m; $\lambda_R = 2$ W/m · K

using these characteristics, we obtain

$$Fo = \frac{a\tau}{R_0^2} = 1{,}14\tau \quad (6)$$

or, as τ = 8760 hours for 1 year,

$$Fo = 10\ \tau^* \quad (7)$$

where τ* – duration of the considered period in years. For example, *Fo* = 5 means that opening was being aired for half a year, *Fo* = 20 – 2 years.

Similarly for numbers *Bi* determination, we obtain

$$Bi = \frac{\alpha R_0}{\lambda_R} = \alpha = \left(\frac{\lambda_{IN}}{\delta_{IN}}\right). \quad (8)$$

For example, if $\lambda_{IN} = 0.1$ W/m · K, *Bi* numbers = 1, 2, 3 will correspond to thickness of layer equal to 0.1 m, 0.05 m and 0.033 m.

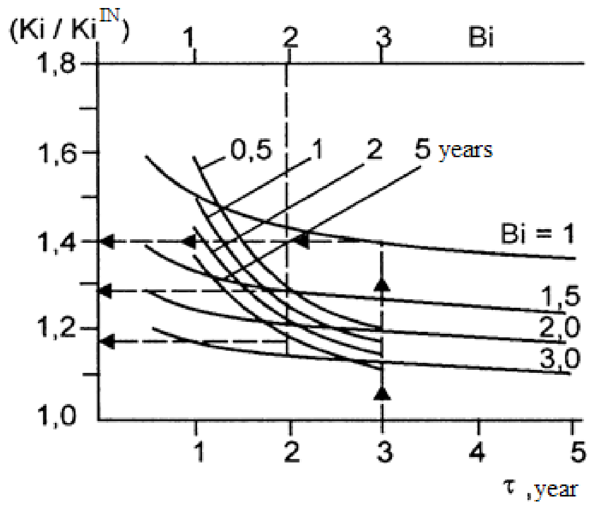

Figure 1. Change of thermal flow in the heat-insulated opening depending on time.

The analysis of curves in Figure shows that from the energy standpoint, thermal insulation is effective even for openings with long service life of τ>2 years, and the higher thermal resistance is, the longer effect size is preserved. For example, in 5 years, the measure of heat flow rate reduction is equal to 1.37 if isolation thickness is 0.1 m, and equals 1.11 if thickness is 0.033. It is naturally that the thermal insulation importance increases significantly for short periods ($Fo \leq 1$). For example, in half a year of opening aeration air with constant temperature, the five-centimeters insulation layer reduces a thermal flow by 1.3 times, and ten-centimeters (Bi=1) layer by 1.6 times. In three years these sizes decrease to 1.2 and 1.4 times respectively. We should not forget that thermal insulation cost is also twice higher. The conducted analysis shows that thermal protection of openings from the energy standpoint is always effective both for short and for long service life of mine openings. Thus, the real effect must be determined on the basis of comparisons of thermal protection variants according to cost performance, i.e. economic effect appears due to a difference of present values of the saved energy during operation, materials and labor costs for construction of heat-protecting layer.

All these arguments referred to the case when properties of the rocks massif surrounding an underground construction are permanent, for example of rocks, which natural humidity is close to zero. As it is noted in work [5], the majority of disperse rocks are characterized by thermophysical properties change in time; that is mainly caused by change of their humidity within an active layer of the opening. The opening active layer is changed from heat-retaining layer into heat-insulating one in course of time. This comes due to rocks openness increase caused by sublimation of free moisture. The humidity annual balance of the air flow is positive for almost all the mines and pits of continuous permafrost zone: the moisture content, which is taken out of the opening due to vaporizing processes, is much higher than moisture content remaining in the openings due to devaporation in summer season [5]. The use of heat-insulating shotcrete in openings reduces degree of rocks drying, as well as the use of other types of thermal insulation or damp-proofing. In this regard, the comparative evaluation of thermal insulation efficiency in heat-retaining openings is of interest. The inevitable question is which is better: the use of heat-protecting shotcrete lining, which will reduce heat-exchange level in the opening, but "keep" heat-retaining properties of the massif, or the use of another lining type, which will leave a heat-exchange surface open, but cause drying of rocks active layer with the course of time. The comparative analysis of two cases was carried out by us in work [4]; it showed reasonability of heat-protecting coatings use for heat-retaining properties retention.

The heat-insulating and heat-retaining layers or their combination have an impact not only on the opening thermal conditions, but also on temperature conditions of surrounding rocks. Thus, this impact is not always obvious. This is not to say definitely how the heat-retaining coating influences the formation of temperature conditions of the rocks surrounding opening, particularly thawing halo size. On the one hand, the heat-retaining layer causes deeper cooling of the rock massif in winter (in comparison with heat-insulating layer being similar on thickness). On the other hand, due to higher coefficient of heat conductivity of heat-retaining layer in thawed state than of similar heat-insulating layer, most likely, the total heat coming to rocks will be higher.

Let us compare two characteristic cases for evaluation of influence of a heat-retaining layer on size of thawing halo of rocks. Two openings with identical characteristics are lined with different materials: the first with porous thermal insulation, and the second with similar but water-saturated thermal insulation, i.e. in the first one, the layer is heat-insulating, and in the second one, it is heat-retaining. Calculations were carried out by means of software package for solution of mining thermophysics problems [6].

Thermophysical properties of thermal insulation material were accepted as follows: λ=0.05 W/m·K, C=1.38 kJ/kg·K, ρ=160 kg/m^3 The heat-retaining layer has the following characteristics: λ_{TH}=0.5 W/m·K, λM=2 W/m·K, W=90%, ρ_{TH}=900 kg/m^3, C_M=2 kJ/kg·K. Air temperature is changed along sinusoid. Temperature is -47°C in January and + 20°C in July. In case of opening section area of 10 m^2 and air low rate of 30 m^3/s, thermophysical properties of rocks are the following: λ_{TH}=1,56 W/m·K, λ_M= 1,7 W/m·K, W = 40%, ρ_{TH}=1800 kg/m^3, C_M= 0,92 kJ/kg·K, C_{TH}=0,86 kJ/kg·K.

The calculations results show that throughout the summer, rocks remain in frozen conditions at a thickness of heat-insulating layer of 0.3 m. The rocks begin to thaw in the middle of June in case of heat-retaining layer of the same thickness.

In case of heat-insulating layer, amplitude of temperature fluctuations of rocks surface on layer border is 7°C (amplitude of annual fluctuations of air temperature is 33.5°C); and at the same thickness, amplitude of temperature fluctuations of rocks on border with heat-retaining layer is equal to 22°C . i.e. it is 3 times higher than at heat-insulation layer.

The similar situation is also observed at layer thickness equal to 0.1 m. For example, the thawing halo round the opening with heat-retaining layer is

0.85 m if the thickness is 0.1 m; it exceeds a thawing halo by 8 times in case of heat-insulating layer of the same thickness. Thus, it is inefficient to apply the heat-retaining layer for reduction of thawing halo, its main purpose is to reduce temperature fluctuations of the incoming air along the length of the opening. However, at the same time, there is a problem of use of the double-layered or multilayered coating, which provides the size reduction of thawing halo and at the same time possesses heat-retaining layer property of temperature fluctuations reduction of the incoming external air.

It is also should be considered that depending on amplitude, the period of temperature fluctuations, and also layer humidity (thermal diffusivity), there may be cases when the heat-retaining layer is close to the heat-insulating layer according the influence on the size of thawing halo. In this case, its immediate purpose, which is adjustment of daily fluctuations of external air temperature, will be minimized. Thus, the most promising direction is creation of the combined coatings consisting of heat-retaining and heat-insulating layers.

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