Wall stoppings optimal parameters selection in underground mine openings

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Abstract
The method of the wall stopping optimum thickness calculation, including thermally-insulated wall stopping separating underground openings with various thermal conditions, was suggested. It was shown that the selection of wall stopping optimal parameters leads to significant energy costs saving for maintaining of the microclimate specified parameters in the mine opening.
Key words: MINE OPENING, WALL STOPPING, DESIGNING, THERMAL CONDITION ENERGY SAVING, OPTIMIZATION, CRYOLITHIC ZONE

The underground facilities separatory wall stoppings are used for the isolation of some mines, such as cameras, from the others. At that, if different specified operating temperatures are set for the openings, for example in such a case, when the specified thermal conditions should be maintained in one of them using electric power installations (calorifiers or refrigerators), the heat or cold is lost through the wall stopping. So, there are additional losses of energy. This problem is especially important when complex using of mine openings in cryolithic zone and also designing and construction of special underground facilities such as underground storages and refrigerators [1, 2, 3].

The wall stopping thickness may be increased in order to reduce the energy loss, but this increases the costs for materials, i.e. production of wall stopping body. Thus, it is necessary to answer the question: what is the optimal thickness of the wall stopping at predetermined energy and materials cost in the region of underground facility installation under specified thermal conditions (temperatures) in separated cambers with wall stopping [4].

The heat flow through the wall stopping is

$$q_o = \frac{(T_1 - T_2)F}{\delta_o / \lambda_o}, \quad \text{W} \qquad (1)$$

where T_1 and T_2 - operating temperatures in the mine openings separated with wall stopping, ^{0}C; F – wall stopping surface area, m^2; δ_o – wall stopping thickness, m; λ_o – coefficient of thermal conductivity of the wall stopping material W/(m K).

Let us assume that q_o is nonproductive loss that increases the power of electric power installations used for conditioning, in particular, maintaining of the specified temperature in the first chamber. I.e., if there was no wall stopping, the installation power for the perfect chamber (without heat loss in the rocks) would be less by q_o. In this case, the total energy loss would be equal to

$E = q_o \tau 10^{-3}$, kW hrs/yr, (2)

where τ – the number of chamber operating hours of the year, hour/year.

Economic losses are equal to

$Ec_e = C_e q_o \tau 10^{-3}$, rub/yr (3)

where C_e – electric energy cost, rub/ kWh.

Using the formulas (1) and (3), we can find the unconditioned costs due to the wall stopping losses:

$Ec_e = \lambda_o (T_1 - T_2) F C_e \tau/\delta_o 10^{-3}$, rub/yr (4)

Whence, it is obvious that by increasing the wall stopping thickness, we reduce the cost of the specified thermal conditions maintaining. On the other hand, at the same time we increase the wall stopping. Costs for the wall stopping construction will be equal to

$Ec_m = C_m F \delta_o K_d$, rub/yr (5)

where C_m - material and labor costs for the wall stopping construction, rub/m^3; K_d - investments depreciation factor, 1/yr.

If all the costs are deducted to the main production of the current year, K_d =1, 1/yr. The results of costs variant calculations for different values of the wall stopping thickness have shown that there is some value δ, wherein minimum of total costs is in evidence. The wall stopping optimum thickness value satisfying the economic costs minimization is at this point. The graphs (Figure) show the calculations results, which obviously demonstrate that there is optimal value of the wall stopping thickness.

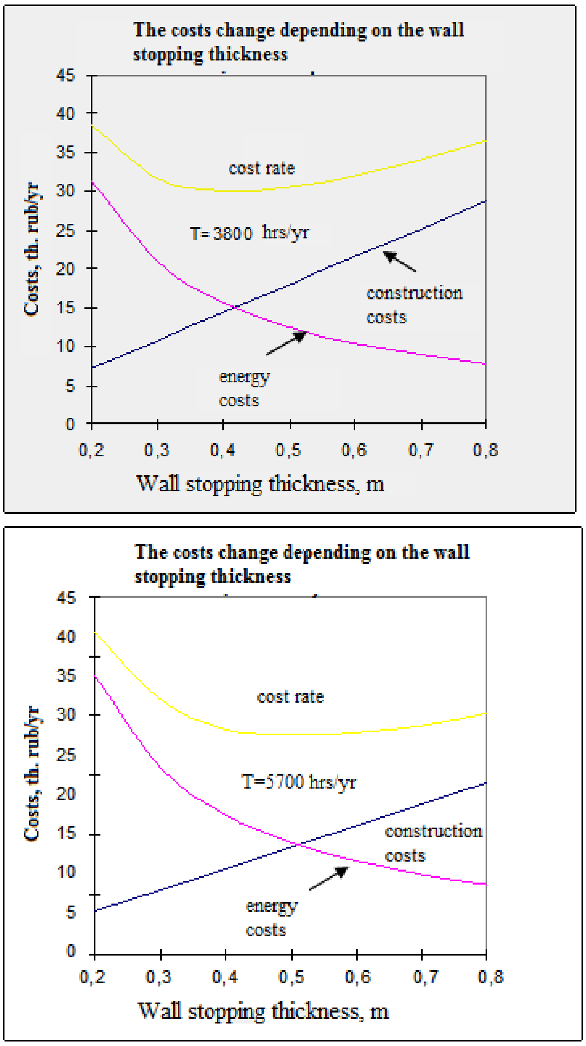

Figure 1. Changes in costs for different operating periods (T) depending on the separatory wall stopping thickness

For optimization problem solving, let us write the objective function of the form

$\Sigma Ec = Ec_m + Ec_e \rightarrow \min$ when $\delta = \delta_{opt}$ (6)

This is a typical problem of unconstrained optimization, the solution of which is found in the form

$$\frac{\partial(\sum 3)}{\partial \delta}\Big|\delta = \delta_{opt} = 0 \qquad (7)$$

Using the previous formulas, let us introduce the expression (6) in the form

$\Sigma Ec = C_1\delta_o + C_2/\delta_o$, rub/yr (8)

$C_1 = C_m K_d F$, rub m/ yr (9)

$C_2 = \lambda_o (T_1 - T_2) F C_, \tau 10^{-3}$ rub m/yr (10)

Substituting (8) into (7) and carrying out the differentiation, we obtain the simple algebraic equation of the form

$C_1 - C_2/\delta^2 = 0$ when $\delta = \delta_{opt}$ (11)

Now, the wall stopping thickness value is easy to find (since the value q is in kW, the product $(T_1 - T_2)\tau$ should be multiplied by coefficient equal to 10^{-3}).

$$\delta_{opt} = \sqrt{C_2 / C_1}\ , \quad \text{m}, \quad (12)$$

$$\delta_{opt} = \sqrt{\lambda_o (T_1 - T_2) C_e \tau / C_m K_{da} 10^3}\ , \text{m} \quad (13)$$

For more convenient further analysis, the formula (13) should be written in the form

$$\delta_{opt} = \sqrt{\left(\frac{C_e}{C_m}\frac{1}{K_d}\right)(\lambda_o (T_1 - T_2))\tau 10^{-3}}\ , \text{m} \quad (14)$$

The first term of radical expression absolutely economic criteria and the second term is technical one determining the chamber operating conditions where there is wall stopping with the specified thermal conductivity.

It follows from the formula analysis that the higher electric energy cost and the lower materials cost is, the heavier wall stopping thickness will be, at that, the operating period is important. For short times, δ_{opt} is equal to the minimal possible thickness calculated from the wall stopping stability conditions or other technological requirements. If it is known that from technological considerations, the wall stopping thickness cannot be smaller than δ_{tec}, the service life period, where optimization problem makes sense, is determined by formula:

$\tau_{pr} \geq (\delta_{rex}\ C_m\ K_d)/(C_e 10^{-3}\ \lambda_o (T_1 - T_2))$, hrs/yr (15)

The costs reduction for air conditioning by means of wall stopping heat insulation is of practical interest. This raises the problem of the optimal thickness value of the heat insulation layer. Let us assume that the wall stopping body thickness is selected from the technological considerations and is δ_o. The wall stopping is made of a material with thermal conductivity coefficient λ_o. Heat losses through the double-layer wall stopping can be determined by the formula

$$q = (T_1 - T_2) F / \left(\frac{\delta_o}{\lambda_o} + \frac{\delta_1}{\lambda_1}\right), \quad \text{W} \quad (16)$$

Following the arguments given when selecting of the optimum single-layer wall stopping thickness, the following optimization problem can be written.

$\Sigma Ec = Ec'_m + Ec'_e \rightarrow \min$, when $\delta_1 = \delta'_{opt}$, (17)

where

$Ec'_m = (C_m \delta_o + C'_m \delta_1)\ F\ K_d$, rub/yr (18)

$Ec'_e = (T_1 - T_2)\ F\ C_e \tau / \left(\frac{\delta_o}{\lambda_o} + \frac{\delta_1}{\lambda_1}\right)$, rub/yr (19)

where C'_m – insulation material cost, rub/m^3, considering the costs of the second wall stopping layer construction; δ_1 – the thickness of the heat insulation layer, m; λ_1 – the thermal conductivity of heat insulation material, W/m K.

In order to find the value $\delta_1 = \delta_{opt}$ the following equation should be solved:

$$\frac{\partial \sum З}{\partial \delta_1} = 0 \quad \text{when} \quad \delta_1 = \delta'_{opt} \quad (20)$$

For convenience, let us write the expression for the objective function in the form

$\Sigma Ec = a_1 + a_2\delta_1 + a_3(a_4 + a_5\delta_1)^{-1}$, rub/yr (21)

where $a_1 = C_m \delta_o F K_d$ (22)

$a_2 = C'_m F K_d$ (23)

$a_3 = (T_1 - T_2) F\ C_e \tau\ 10^{-3}$ (24)

$a_4 = (\delta_o/\lambda_o)$ (25)

$a_5 = (1/\lambda_1)$ (26)

Solving the problem (20), after differentiation, we obtain the following algebraic equation:

$[a_2(a_4 + a_5\delta_1)^2 - a_3 a_5] = 0$ when $\delta_1 = \delta'_{opt}$ (27)

a solution of which does not cause difficulty:

$$\delta'_{opt} = \sqrt{\frac{a_3}{a_2 a_5}} - \frac{a_4}{a_5}, \quad \text{m} \quad (28)$$

Substituting the value of the coefficients a_i from (25)-(29) into (31), we finally obtain

$$\delta'_{opt} = \sqrt{\frac{(T_1 - T_2)\lambda_1 C_e \tau 10^{-3}}{C'_m K_d}} - \left(\frac{\lambda_1}{\lambda_o}\right)\delta_o, \quad \text{m} (29)$$

Comparing the expressions (14) and (29), we can see that they differ on the value of the second term, i.e. expression (14) is a special case of the more general expression (29) for determining of the double-layer wall stopping optimal thickness at a fixed base layer thickness.

The wall stoppings separating the chambers with a positive temperature from refrigerated chambers with low negative temperatures are of particular interest. For example, the storage temperature of biological materials in the refrigerator chambers should be below or equal to -40 ^{0}C. In these and many other cases of practical interest, it is reasonable to use the ice instead of heat insulation, as it is cheap and convenient material. In this case, the wall stopping is double-layer: it is made of traditional support material from the "warm" chamber side and of ice from a "cold" one. The natural constraint of such wall stoppings effective use is that the contact temperature between two layers is equal to the ice melting temperature, i.e.:

$T_b = T|_{\delta=\delta o} \geq T_{mel}$, ^{o}C (30)

In the steady state case, the value of T_b can be found from the expression

$T_b = T_1 - q\ \delta_o/\lambda_o$, ^{o}C (31)

The heat transfer rate value is determined by the formula

$$q = \frac{T_1 - T_2}{\frac{\delta_o}{\lambda_o} \oplus \frac{\delta_{ice}}{\lambda_{ice}}}, \quad \text{W/m}^2 \qquad (32)$$

where δ_{ice}, λ_{ice} –the thickness and the thermal conductivity of ice respectively, m; W/m K. Simultaneous solution of (31) and (32) leads to the equation

$(T_1 - T_{mel})\ \lambda_o/\delta_o = (T_1 - T_2)/\ (\delta_o/\lambda_o + \delta_{ice}/\lambda_{ice})$ (33)

Parameter δ_o can be found from (29). In this case, it is conveniently to write it in the form

$$\delta_{ice} = \sqrt{\frac{(T_1 - T_2)\lambda_{ice} C_e \tau 10^{-3}}{C_{ice} K_d}} - \left(\frac{\lambda_{ice}}{\lambda_o}\right)\delta_o, \text{ m}, \qquad (34)$$

where C_{ice} – material and installation costs of the wall stopping ice layer, rub/m^3.

Simultaneous solution of (33) and (34) leads to the equation for determining of the value δ_o satisfying (30)

$$\delta_o = \lambda_o \left(\frac{T_1 - T_{mel}}{T_1 - T_2}\right) \sqrt{\frac{(T_1 - T_2) C_e \tau 10^{-3}}{C_{ice} \lambda_{ice} K_d}}, \text{ m} \qquad (35)$$

Optimal wall stopping should consist of two layers, which are δ_o and δ_{ice} in thickness, and the value of which is determined from (35) and (34) respectively.

Example. There is a wall stopping consisting of concrete and ice. Initial data: λ_o = 1,28 W/m K; λ_{ice} = 2,2 W/m K; T_1 = +18^{o}C; T_2 = -18 ^{o}C; C_{ice} = 1000 rub/m^3; C_e = 3 rub/kWh; τ = 3800 hrs/yr; K_d = 1, 1/yr; T_{mel} = 0 ^{o}C. Determine the optimal value of δ_o and δ_{ice}.

By the formula (35), we find

$$\delta_o = 2.2\left(\frac{18-0}{18+18}\right)\sqrt{\frac{(18+18)3 \cdot 3800 \cdot 10^{-3}}{1000 \cdot 2.2 \cdot 1}} = 0.276 \text{ m}$$

By the formula (34), we find

$$\delta_{ice} = \sqrt{\frac{(18+18)2{,}2 \cdot 3 \cdot 3800 \cdot 10^{-3}}{1000 \cdot 1}} - \left(\frac{2{,}2}{1{,}28}\right)0{,}276 = 0{,}474$$

m

Using equations (31) and (32), we obtain

$$T_b = T_1 - \frac{(T_1 - T_2)\delta_o / \lambda_o}{\frac{\delta_o}{\lambda_o} + \frac{\delta_{ice}}{\lambda_{ice}}}, \quad ^o\text{C} \qquad (36)$$

From where, we define the desired temperature at the boundary

$$T_b = 18 - \frac{(18+18)0.276/1.28}{0.276/1.28 + 0.474/2.2} = 18 - 18 = 0^o \text{ C}$$

Thus, the wall stopping, which is optimal according to economic and technological parameters, must consist of concrete layer of 0.28 m and ice layer of 0.47 m. It is naturally that from technological stability considerations, if the wall stopping concrete layer, for example, cannot be less than δ_{tec}= 0.3 m, then this value is selected, and as $\delta_{tec} > \delta_o$, the condition (30) will be fulfilled automatically.

Further researches of this problem should be directed to generalized mathematical model development for selecting of optimum parameters of the wall stoppings consisting of any quantity of layers with different thermal properties. Including the wall stopping made of materials that change their aggregative state at the temperature changes.

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