Efficacy evaluation of heat-exchange opening aeration non-stationary mode

Aleksandr Galkin

D.Sc. in engineering
Saint-Petersburg, National Mineral Resources University

Abstract
The evaluation of heat-exchange opening aeration non-stationary (cyclic) way was carried out. This way provides for opening aeration during given period of time divided into various duration intervals, where the air rate is constant, and in different intervals is different, and intervals repeat cyclically. The opening cyclic aeration was compared with constant rate continuous in order to determine the energy efficiency. The quantity of cold which is saved in the solids during given period of time when airing of the opening with a constant rate was used as criterion. On the basis of mathematical modeling, the main consistent patterns of thermal mode formation in the rocks surrounding the opening at a cyclic way of aeration were established. It is shown that if there is no time restriction, the non-stationary mode of aeration allows achieving of the purposes at much smaller energy input than the mode of continuous aeration.
Key words: AERATION, THERMAL MODE, MINE OPENING, ENERGY EFFICIENCY, MATHEMATICAL MODELING

Introduction

The problems of the ventilating mode optimum parameters selection when airing of the opening raise, for example, if it is necessary to determine the period duration and quantity of the air given to the opening for ensuring of their stability or for minimization of expenses for microclimate standard parameters development [1, 2, 3, 4]. This task is no less relevant when constructing and reconstructing of underground facilities of different function and mine openings complex using [5, 6, 7]. The researches of thermal mode formation processes at non-stationary (cyclic) aeration of heat-exchange modules of underground refrigerators, vegetable storehouses, geo technical conditioning system, i.e. where it is necessary to save the maximum quantity of cold (heat) in solids for a certain period of time at minimum of ventilation power costs are of great interest [8, 9, 10, 11, 12].

Problem statement

Cyclic (non-stationary) aeration is the opening aeration during given period of time divided into various duration intervals, where the air rate is constant, and in different intervals is different, and intervals repeat cyclically. The opening cyclic aeration was compared with constant rate continuous one in order to determine the energy efficiency. When carrying out of researches, as comparative functions we used the following:

- total costs of opening ventilation when cyclic and continuous airing;
- increase (reduction) in the general duration of opening aeration for achievement of the specified criterion of quality;
- decrease (increase) in duration of intensive aeration (aeration with the maximum air rate).

The quantity of cold, which is saved in the solids of opening active layer during given period of time at continuous opening aeration with constant rate, was used as criterion of quality.

The problem was formulated in the following statement. There is a heat-exchange opening, for example, of the underground refrigerator with the set geometrical parameters – perimeter, section and length; it is aired with a constant rate of V_0 and temperature t_0 during a certain time period $\sum \tau_0$. During this time period, the temperature of rocks goes down, i.e. the certain cold quantity is collected in the solids surrounding the opening, and it is equal to Q_0. Economic expenses for accumulation of this quantity of cold are defined by opening ventilation costs $\sum Z_0$ [13]. In the second case, the similar opening, which was aired cyclically was considered; i.e. the entire period of aeration was divided into the intervals equal to τ_c, and they was divided into two more intervals, which are nominally called as working hours of ventilation system τ_w and rest time τ_r. That is $\tau_c = \tau_w + \tau_r$, and the general opening aeration was equal to $\sum \tau = K\tau_c$, where K — some integer number defined from the equation $Q_0 = Q_c$, where Q_c – cold quantity, which is saved by solids at cyclic aeration. Opening air temperature was same as in the first case, and air rates during the periods of τ_r and τ_w were various, and $V_w >> V_r$ or $V_r = 0$. It is naturally that the last condition fulfillment is possible only with those objects, where continuous aeration is not provided by safety norms. The main idea of this computing experiment is to find out whether it is possible to save the same cold quantity with cyclic aeration during the same period of time as when continuous airing if the air flow rate is increased in the period of τ_w, and then, is reduced sharply, or if the ventilation is stopped in the period of τ_r. It was also interesting how the general duration of the ventilation period at opening cyclic aeration will be changed if the maximum period rate of the interval of τ_w is equal or less than the rate of the ventilation stream when continuous airing, i.e. $V_w << V_0$ when $V_r = 0$. It is obvious that, in this case, cyclic aeration will be effective only if the condition $\sum Z \le \sum Z_0$ is satisfied under restriction $\sum \tau \le \tau^*$, where $\sum Z$ — cyclic aeration ventilation costs, which are equal to KZ_C, τ^* — technological time restriction. The last parameter plays an important practical role; because, theoretically, selecting the corresponding ratios of τ_w / τ_r, duration of the cycle τ_c and rates V_w and V_r, it is always possible to achieve the fulfillment of condition $\sum Z \le \sum Z_0$, but the value $\sum \tau$ will be much higher than $\sum \tau_0$. This results from the fact that the costs of ventilation are expressed by functional dependence of the form $Z = f\left(\tau, V^3\right)$, i.e. depends linearly on time, and from rate, this dependence has a cubic appearance.

On the other hand, if it is necessary to save necessary cold quantity in the solids for the given period of time τ^*, how it is better to do this: a) to air the opening constantly with some rate V_0 during the entire period τ^*; b) to air the opening constantly with some rate $V_{air} > V_0$, but during the smaller period of time $\tau_{air} < \tau^*$; c) to use cyclic airing, having chosen such ratios τ_w/τ_r, and values τ_c, V_w and V_r in order to satisfy the condition $\sum \tau \le \tau^*$.

It is natural that the main criterion of all the options efficiency is minimization of aeration costs at obligatory achievement of the specified quality criterion. It should be noted that in some practically interesting cases, cyclic aeration is a compulsory measure, and not only τ^* is specified, but also the size τ_c, and even the ratio τ_r/τ_w. For example, when underground refrigerator rock cooling, in the daytime when people work inside, the air rate is limited or cooling is not carried out (active aeration is carried out at night). Similarly, the periods of active ventilation when openings boring are connected with cycles of boring works. In this case, only the air rate, on which the additional restrictions determined by safety rules of mining and underground facilities operation are placed, can serve as the control parameter.

Researches results

Let us carry out the analysis of researches results on the actual example of the task solution by means of the program complex developed under the author guide [13, 14]. The aeration cases of the heat-exchange opening, which is driven in frozen rocks with the temperature conductivity coefficient of $1.1 \cdot 10^{-6}$ m^2/s of 100 m length with the equivalent radius equal to 2 m, and with the aeration rate of 4 m/s (1st case) and 0.4 m/s (2nd case), and when cyclic airing with interval τ_c = 24 hours when $\tau_w = \tau_r$ =12 hours (3rd case), are considered. The calculations results of air-inlet temperature equal to -20°C and the natural solids temperature equal to -5°C, and during 96 hours of opening aeration under the air rate of 4 m/s and rate of air of 0,4 m/s shows that tenfold reduction of air stream rate causes a wall temperature increase by 1.5-1.6 times. The openings temperature at a depth of 0.4 m increases by the same value. During the same period of time at cyclic aeration of $V(\tau_w)$=4 m/s and $V(\tau_r)$=0.4 m/s, rocks temperature at a depth of 0.4 m -10°C (at constant V=4 m/s — -12°C), which is 1.2 times higher. The same value is obtained for the mine opening surface temperature.

In particular, the obtained ratio shows that we reduce the opening cooling rate by only 1.2 times when reducing of intensive ventilation time twice under opening cyclic aeration. It is also established that, as time passes, the cyclic aeration efficiency increases in comparison with simple rate reduction, i.e. temperature change rate is higher for a cyclic case on the opening wall, as well as in depth, than for a case of simple rate reduction. For example, the average rate of cold accumulation during the first 5 days when opening airing with the maximum rate is 11.5 GJ/h, with the minimum one – 6.9 GJ/h, and when cyclic airing – 10.1 GJ/h. I.e. it is obvious that efficiency of aeration cyclic way is much higher in comparison with the rate simple reduction.

The rocks temperature changes in depth are given at various time points in Fig. 1 when cyclic airing.

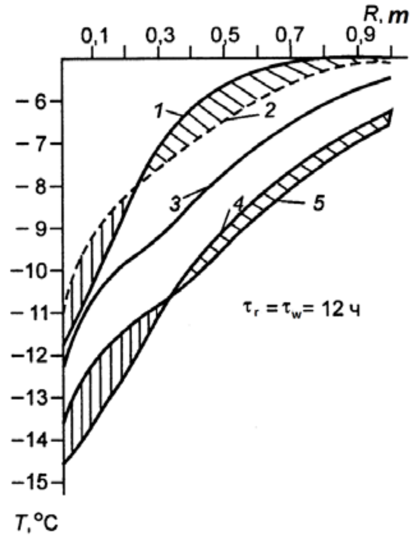

Figure 1. Rocks temperature change in depth at cyclic aeration.
1 – in 12 hours; 2 – in 24 hours; 3 – in 48 hours; 4 – in 84 hours; 5 – in 96 hours.

From diagrams, it can be seen that temperature increases in a marginal layer while at a depth of 0.2-0.3 m and further it is reduced when changing of the aeration mode during cycle. With cycles number increase, some increase of an active layer is observed, but at that, the absolute temperature is reduced both on the opening wall and in an active layer.

The cold quantity change (GJ) accumulated by solids when continuous and cyclic airing is presented in Fig. 2.

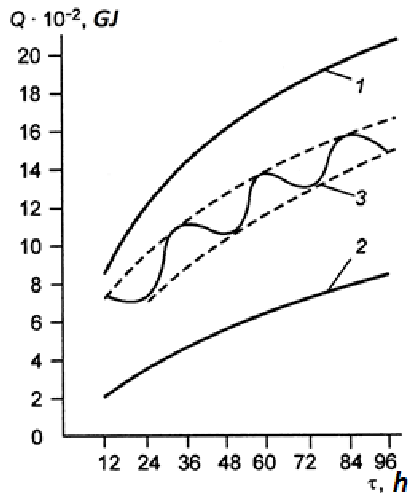

Figure 2. The quantity change of cold accumulated by solids depending on the air rate and duration of aeration.
1 – at air rate of 4 m/s; 2 – at air rate of 0.4 m/s; 3 – at cyclic aeration of 12 hours interval.

As is seen from diagram, the tendency to cold accumulation increase at reduction of aeration duration with the maximum rate is observed at cyclic aeration. That is, the middle curve line 3 passes not between the 1st and 2nd curve in the middle, but closer to the 1st which points to the energy efficiency of cyclic aeration. It can be explained by the following effect: it is known that the thermal stream is proportional to difference of air and opening wall temperatures, and as time passes, it is reduced, as $T_{wall} \rightarrow t_{op}$, and gradually, in a certain period, the heat exchange level comes to the certain quasi-stationary level determined by solids air heat-transfer coefficient and solids thermophysical properties: the higher solids heat conductivity is, the longer period will be. When continuous airing, the wall temperature is reduced very quickly, and in 96 hours, practically comes to quasi-stationary level. When cyclic airing, the wall temperature change rate is rather high at any time point of intensive aeration, and, therefore, thermal stream is higher. Although, the wall temperature on a final time point in absolute value is nearly three degrees higher. The total cold quantity, which is saved by solids, tends to increase. i.e. if all the cold quantity, which is saved by solids during continuous aeration, is conditionally shared for two, the obtained value will be less than that cold quantity, which will be saved by solids when cyclic airing with the general time of intensive aeration of $\sum(\tau_w)$ equal to a half of the continuous aeration period. The following inequation is correct:

$0.5Q_0(\tau_0) \leq Q_c\ (\sum\tau_w = \tau_0/2)$,

where Q_c — the cold quantity, which is saved by solids when cyclic airing for the total period of intensive aeration, equal to $\tau_0/2$; Q_0 —the cold quantity, which is saved by solids during continuous aeration, equal to τ_0.

The numerical calculations results given in the form of diagram in Fig. 3 can serve as proof of this consistent pattern.

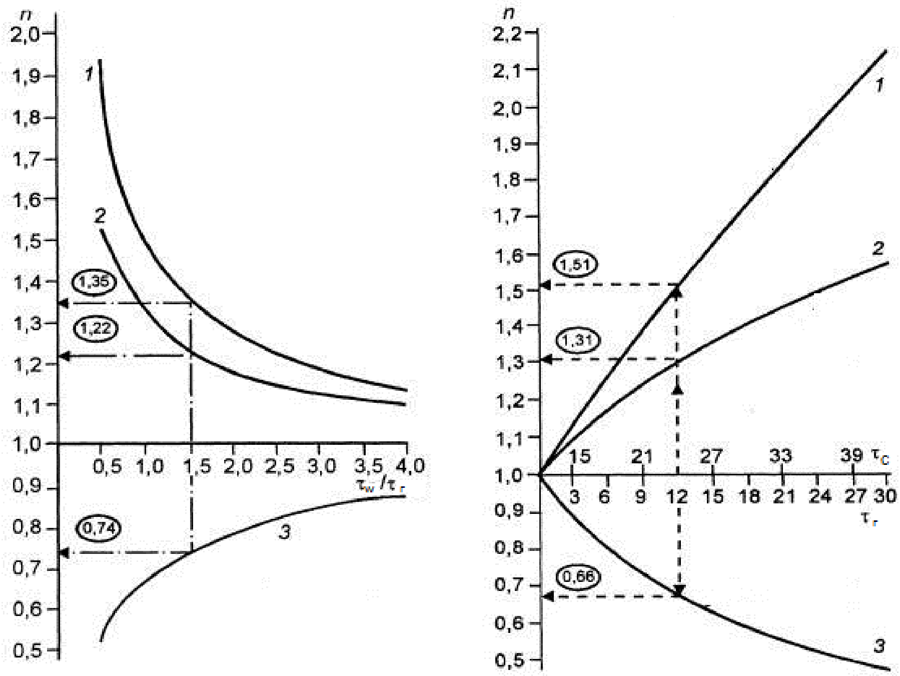

Figure 3. Comparison of the mine opening cyclic and constant aeration modes characteristics at various periods of a cycle for obtaining of identical cooling level of surrounding solids.1 – the degree of costs reduction (economy); 2- degree of increase in the aeration general duration; 3- degree of decrease in intensive aeration duration.

Three comparative characteristics of process are considered as the main ones: the degree of decrease in economic costs of opening ventilation; degree of increase in the general duration of aeration; degree of decrease in duration of intensive aeration. As is seen from diagrams, the curve characterizing the degree of decrease in economic costs runs above the curve characterizing degree of increase in the general duration of aeration, i.e. the economic efficiency of an aeration cyclic way is always higher than its characteristics deterioration due to increase in necessary time for quality criterion achievement. Under equation $(\tau_w/\tau_r) = 4$, the economic efficiency of this method is insignificant. The analysis of curves in Fig. 3-A shows that under known value τ^*, it is possible to select such ratio (τ_w/τ_r), which provides for the economic efficiency of the method. The lower curve in Fig. 3-A characterizes the ratio $\sum(\tau_w)/\tau_0$, i.e. the total time of intensive aeration at a cyclic way to the time of aeration with constantly high rate. When decreasing of the ratio (τ_w/τ_r), the degree of decrease in duration of intensive aeration is reduced, and, therefore, the economic efficiency of opening ventilation cyclic way use increases. The same comparison characteristics for the evaluation of cyclic way efficiency depending on duration of one cycle during the general time of $\sum\tau_0 = 720$ hours at the constant period of the intensive aeration equal to τ_w = 12 hours, are given in Fig. 3-B. The value τ_r was variable and changed from 3 to 30 hours. The results presented in the form of diagrams in the Figure show that if there is a technological capability of increase in the opening aeration general time, the ventilation cyclic way use is always economically sound. So, if it is possible to increase the total period of opening ventilation from 720 to 940 hours, the ventilation cyclic way use with $\tau_w = \tau_r = 12$ hours will allow reducing of rocks cooling costs by 1.5 times to the necessary level. At that, duration of air blower total operating time will be only 0.66 of the general duration of operation at the aeration constant mode.

Conclusions

Considering the results of the conducted researches, it is possible to make a conclusion that the non-stationary (cyclic) way of aeration is the effective control tool of temperature condition of the rocks surrounding the openings for accumulation of the maximum quantity of cold (heat) within an active layer of heat exchange opening. This way allows significant reducing of energy and material costs by creation of the given thermal mode and can be recommended for use when designing and operating of heat-exchange openings of different function underground facilities.

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