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# REDUCTION OF THE RISK OF SELECTING THE EMERGENCY VENTILATION MODE THROUGH LOCAL CONTROL OF VENTILATION FLOWS

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**Abstract**. The implementation of measures regarding the organization of emergency ventilation of mine is connected with various types of risks, as in other cases of the operation of high-risk enterprises. In particular, this applies to the emergency risk that arises when there is a need for the emergency evacuation of people from the mine workings, gassed with fire products (that is, the risk of their poisoning or damage due to the thermal factor) and the emergency risk that is provoked by the wrong choice and implementation of the emergency ventilation mode. Both types of risks require to reduce the use of means of ventilation - main and local ventilation fans. Provision should also be made for the use of various passive control devices. The main result of the methodological approach used today is the selection of the emergency ventilation mode, which maximally limits the gassing zone of the mine ventilation network with gaseous combustion products. At the same time, the criterion for the effectiveness of the emergency evacuation of miners should be the maximum use of non-gasified workings, which achieves the goal of managing ventilation in the event of accidents.

The proposed control function, which characterizes the degree of risk of distribution of fire gases in mine workings, is the root mean square deviation of the concentration of fire gases in the controlled branches of the network from the required level of stabilization. For two control devices and two controlled areas, it is part of a three-dimensional cone, and the control region is bounded by two hyperbolas. The problem formulation looks similar when the size of the base of the regulating devices is increased . A limitation on the task is formulated, and a conclusion is made regarding the possibility of applying analog methods of dynamic programming for its solution. As such, the multi-step optimization method, the one-step optimization method, and the extreme coordinate optimization method (the last one is the most effective) are considered. The greatest efficiency of their use will be achieved with the introduction of an automated ventilation control system, which provides feedback from the means of regulation and regulatory devices.

**Keywords**: emergency risk, aerological risk, management functionality, regulatory devices, exogenous fire.

## 1. Introduction

The occurrence of an exogenous emergency makes certain adjustments to the ventilation strategy of an underground mining enterprise. The implementation of these measures is connected, as in other cases of the operation of high-risk enterprises, with various types of risks. In particular, this refers to the emergency risk that arises when there is a need for emergency evacuation of people from mine workings, gassed by fire products (that is, the risk of their poisoning or damage due to the thermal factor) and aerological risk, which is provoked by the wrong choice and implementation of the emergency ventilation mode (EVM).

Both types of risks require to reduce the use of means of ventilation - main fans (MF) and local ventilation. The use of various passive control devices (CD) should also be provided for.

The main result of the methodological approach used today is the selection of the EVM, which maximally limits the gassing zone of the mine ventilation network (MVN) with gaseous combustion products [1-4].

At the same time, the criterion for the effectiveness of the emergency evacuation of miners should be the maximum use of non-gasified workings, which achieves the goal of managing ventilation in the event of emergencies.

However, the main emphasis is placed on ensuring the supply of the necessary amount of air to emergency and dangerous workings on the control of the MF.

Being a universal means of regulation, the MF at the same time can exert an unacceptably strong influence on the MVN, since the regulation is of a global nature.

In some cases, such regulation can overturn ventilation jets in unstable workings and undesirably gassing non-emergency areas of the MVN. Therefore, in some cases, local regulation is more effective

The purpose of the article is to substantiate the methodology for choosing the emergency ventilation mode by local control of ventilation flows, and *the task of the article* is to briefly describe the developed method and algorithm [5,6].

## 2. Methods and results

Since the extreme case - ensuring complete degassing of emergency and dangerous workings during a fire - is practically unattainable, the main goal of ventilation control in this case may be to reduce the concentration of fire gases $C_t(i,j)$ in a number of workings *(i,j)* to the permissible level $C_{ul}$; in other words, it is desirable to fulfill the condition for each gassed working and at each moment of time $t$

$$0 \le C_t(i,j) = \frac{q(i,j)}{Q(i,j)} \le C_{ul},$$

where $q(i,j)$, $Q(i,j)$ are the flow rate of fire gases and air consumption in *(i, j)*.

If we consider the mine as a whole, then the functionality of the management goal, which characterizes the distribution of fire gases by its workings, can be presented in the form:

$$F = \left\{ \frac{1}{l} \sum_{k=1}^{p} \left[ C_{ul} - C_t(i_k, j_k) \right]^2 \right\}^{\frac{1}{2}} \to \min, \tag{1}$$

where $l$ is the number of control points $C_t(i,j)$ (it is implied that a one-to-one correspondence between mining workings and such control points has been established); $p$ is the number of control points where $C_t(i,j) \ge C_{ul}$.

It is the root-mean-square deviation of the concentration of fire gases in all controlled *(i,j)* from the required level of stabilization. In the general case, $l \ne p$.

For the completeness of the statement of the task, the limitations imposed by the possibilities of the MVN and [1] should be considered. These include:

a) correlation coefficient $k_s(i_l,j_l)$, which characterizes the relationship of aerodynamic parameters of workings [4]:

$$\Delta Q(i_l, j_l) = k_s(i_l, j_l)\Delta Q_s, \tag{2}$$

where $\Delta Q(i_l,j_l)$ is the change in air flow in $(i_l,j_l)$, caused by a change in the state of the $s$ CD (increasing the air flow in the working, where it is installed, by $\Delta Q_s$);

b) dependence of the relative flow of air flowing through the CD on its position $\Delta R_p(i,j)$:

$$f(\Delta R_p) = \frac{Q_p^0(i,j) - Q_p(i,j)}{Q_p^0(i,j)} = \left\{1 - \exp\left[d \cdot \Delta R_p(i,j) \cdot \frac{Q_p(i,j)}{Q_p^0(i,j)}\right]\right\},$$

where $Q_p^0(i,j)$ – air flow through the CD set in *(i,j)*, when it is fully opened $(R_p(i,j)=0)$; $Q_p(i,j)$ – air flow through the CD located in an intermediate position $(\Delta R_p(i,j)\neq 0)$; $d$ is the approximation coefficient, which is determined experimentally;

c)

$$R(i,j) = \begin{cases} \overline{R(i,j)}, & (i,j) \in V_p \\ R(i,j), & (i,j \notin V_p) \end{cases}, \qquad \overline{R(i,j)} = R(i,j) + \Delta R_p(i,j),$$

where $V_p$ is the set of workings of MVN, in which CD is installed;

d) $\Delta R_p(i,j) \geq 0,\ (i,j) \in Vp$;

e) $Q_{min} \leq Q(i,j) \leq Q_{max}$, where $Q_{min}, Q_{max}$ are permissible limit values of air flow in *(i,j)* according to [1];

f) minimum energy consumption, which is achieved by reducing the total amount of air supplied to the mine: $Q_{gen} \to min$.

g) ensuring the economic and sustainable operation of the MF by supporting its depression in the region

$$\begin{matrix} a_0Q^2(i,j)+b_0Q(i,j)+C_0 \\ a_1Q^2(i,j)+b_1Q(i,j)+C_1 \end{matrix} \leq H(i,j) \leq \begin{matrix} a_2Q^2(i,j)+b_2Q(i,j)+C_2 \\ a_3Q^2(i,j)+b_3Q(i,j)+C_3 \end{matrix} \qquad (3)$$

where $a_0,\ b_0,\ c_0 \ldots\ a_3,\ b_3,\ c_3$ are coefficients of the pressure characteristics of the MF, characterizing the area of its economic and sustainable operation.

Taking into account these limitations, the solution of the formulated problem is reduced to the determination of the provisions of the CD, which ensure the distribution of air in the MVN, at which the functional given by expression (1) reaches its possible minimum. The exact solution of such problems is not possible, and analog methods of nonlinear programming can be used to solve them.

Let's consider the geometric interpretation of the problem (fig. 1). For simplicity of illustration, consider the case of control in the presence of two ($l = 2$) sections with $C_t(i,j) \neq 0$ and two CD, the installation locations (base) of which are determined in advance.

The objective functional in this case is part of three-dimensional cone, the global minimum of which corresponds to a point on the phase plane with coordinates ($c_1$,

$c_2$). All the considerations given below are also valid in the case of a larger task dimension; the goal functional in this case takes the form of a $l$+1 – dimensional cone.

It should be noted that $q(i,j) \neq const$ during air distribution control. Indeed, an increase in $Q(i,j)$ arriving at the fire source causes an activation of the combustion process, hence an increase in $q(i,j)$ both in the fire source and, of course, during the spread of fire gases. Decreasing $Q(i,j)$ has the opposite effect.

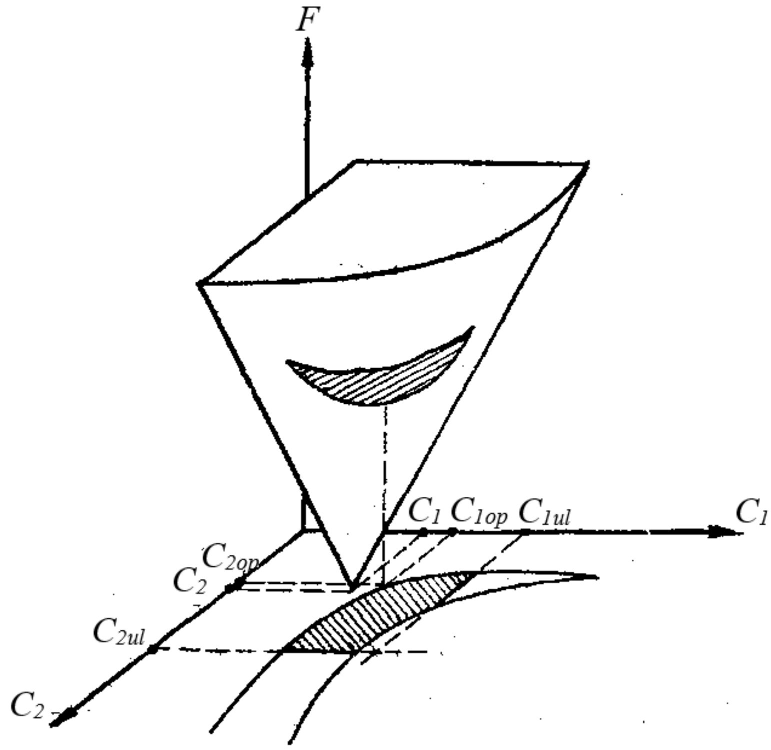


Figure 1 – An example of controlling two-CD

So,

$$\Delta q(i,j) = (i,j)\Delta Q(i,j) \tag{4}$$

and $C_{t_1}(i,j) \neq C_{t_2}(i,j)$; in the general case

$$C_t(i,j) = \frac{q(i,j)+\Delta q(i,j)}{Q(i,j)+\Delta Q(i,j)}, \tag{5}$$

where $q(i,j)$, $Q(i,j)$ are the flow rate of fire gases and air flow in $(i,j)$ to control; $\Delta Q(i,j)$, $\Delta q(i,j)$ – increase in air flow and the resulting increase in fire gas discharge.

Let's determine the type of dependence between the values of $q(i,j)$ on both controlled sections from the change in $Q(\mathrm{i},j)$ through the *s-th* CD, provided that the remaining CD in the MVN are fully open. The place of installation of the *s-th* CD is not discussed, i.e. it can be both on one of the plots and outside them.

The concentration of fire gases at the sites ($i_1, j_1$) and ($i_2, j_2$) at the initial moment of time is equal to

$$C^0(i_1, j_1) = \frac{q(i_1,j_1)}{Q^0(i_1,j_1)} \qquad C^0(i_2, j_2) = \frac{q(i_2,j_2)}{Q^0(i_2,j_2)}.$$

Let's conditionally move the CD from a fully open to an intermediate state, which is equivalent to increasing the air flowing through it by the amount of $Q_s$. According to (2), this leads to a change in air flow in areas:

$$\Delta Q(i_1, j_1) = Q^0(i_1, j_1) + k_s(i_1, j_1)\Delta Q_s$$

$$\Delta Q(i_2, j_2) = Q^0(i_2, j_2) + k_s(i_2, j_2)\Delta Q_s,$$

and, as a consequence (5) - to a change in the concentration of fire gases

$$C_t(i_1, j_1) = \frac{q(i_1,j_1)+\Delta q(i_1,j_1)}{Q^0(i_1,j_1)+k_s(i_1,j_1)\Delta Q_s}$$

$$C_t(i_2, j_2) = \frac{q(i_2,j_2)+\Delta q(i_2,j_2)}{Q^0(i_2,j_2)+k_s(i_2,j_2)\Delta Q_s}$$

But, taking into account (4),

$$\Delta q(i_1, j_1) = \bar{k}(i_1, j_1) \cdot k_s(i_1, j_1) \cdot \Delta Q_s$$

$$\Delta q(i_2, j_2) = \bar{k}(i_2, j_2) \cdot k_s(i_2, j_2) \cdot \Delta Q_s$$

Carrying out the necessary transformations, we get $C_t(i_1, j_1) = \frac{t_1 - C_t(i_2,j_2) \cdot t_2}{t_3 - C_t(i_2,j_2) \cdot t_4}$,

where

$$t_1 = \bar{k}(i_2, j_2) \cdot k_s(i_2, j_2) \cdot q(i_1, j_1) - \bar{k}(i_1, j_1) \cdot k_s(i_1, j_1) \cdot q(i_2, j_2);$$

$$t_2 = q(i_1, j_1) \cdot k_s(i_2, j_2) + Q^0(i_2, j_2) \cdot \bar{k}(i_1, j_1) \cdot k_s(i_1, j_1);$$

$$t_3 = Q^0(i_1, j_1) \cdot k(i_2, j_2) \cdot k_s(i_2, j_2) + k_s(i_1, j_1) \cdot q(i_2, j_2);$$

$$t_4 = Q^0(i_2, j_2) \cdot k_s(i_1, j_1) - Q^0(i_1, j_1) \cdot k_s(i_2, j_2).$$

Thus, the desired dependence is hyperbolic, and the controllability area (Fig. 1) for the case of two controlled areas and two CD in the network is limited by two hyperbolas. In the general case, the number of hyperbolas limiting the controllability region is equal to the number of the CD in the MVN. Other boundaries of the controllability area are determined by the constraints imposed on the system ($C_{1ul}$, $C_{2ul}$). It should be noted that, in the general case, the point ($C_1$, $C_2$) that determines the global minimum may not belong to the controllability region ((as shown in Fig. 1). This is determined by the capabilities of the MVN, the operating mode of the MF and the imposed restrictions. And here the definition control region of the point with coordinates ($C_{1ul}$, $C_{2ul}$), in which the functional $F$ reaches its possible minimum, is the first stage of solving the problem.

The second stage can be the use of the capabilities of the managed MF. An increase in its productivity by $\Delta Q_в$ leads to an increase in air consumption in all mine workings by

$$\Delta Q(i,j) = k_в(i,j)\Delta Q_в, \tag{6}$$

where $k_в(i,j)$ is the correlation coefficient of the MF and working ($i,j$).

An increase in air flow through the MF leads to an expansion of the controllable area; carrying out regulation in this way, it is possible, in principle, to expand the area of control to such limits that the point ($C_1$, $C_2$) will be inside it. But there may also be cases when:

a) the MF reserves are not exhausted, but due to the existing restrictions, the point ($C_1$, $C_2$) cannot enter the regulation area;

b) MF reserves are exhausted, but the regulation area has not expanded enough, and the point ($C_1$, $C_2$) does not fall into it;

c) MF reserves are not completely exhausted, but with a further increase in $Q_v$, MF leaves the zone of sustainable and economic operation (3).

In these cases, the MVN reserves are completely exhausted and control is reduced to finding the local minimum point ($C_{1ul}$, $C_{2ul}$).

The ability of MF to change the control area can also be used if $C_t(i,j)<C_{pr}$ in all controlled sections, i.e. the control function is zero. In this case, it is expedient to reduce $Q_v$ until ($C_1$, $C_2$) is within the controllability region constructed taking into account all restrictions.

Thus, when solving the problem, two goals are fulfilled: achieving the optimal air distribution in the air conditioning system with the minimum possible air consumption, i.e. with minimum energy consumption for ventilation.

Solving the problem by analog methods of nonlinear programming is an iterative process, for which it is necessary to know the state of the control object after each successive iteration. If we divide the range of change of function $f(\Delta CD)$ into $N$ equal intervals, each of which will determine the relative change of air flow rate $\Delta$ through CD, then $f_0(\Delta CD)=N_0\Delta, \ldots, f_k(\Delta CD)=N_k\Delta, \ldots, f_N(\Delta CD) = N_N \Delta$,, or, otherwise,

$$f_{k\pm1}(\Delta R_p) = N^{k\pm1} \cdot \Delta,$$

where $f_{k\pm1}(\Delta R_p)$ – the value of the function $f(\Delta CD)$ at point $k$; $Q^{N_0}$ – air consumption through the CD when it is fully opened, i.e. in zero ($N_0$) position; $Q^{N_k}$ – air intake through the CD, which is in the $k$-th position; $N_k$ – the position of the CD, which corresponds to the value of the resistance $Q^{N_k}$.

Solving the resulting system of equations with respect to $Q^{N_{k\pm1}}$, we obtain

$$Q^{N_{k\pm1}} = \frac{Q^{N_k}\left(100 - N^{k\pm1} \cdot \Delta\right)}{100 - N^K \cdot \Delta}.$$

With the help of this formula, it is possible to calculate the new air flow rate through the CD after each iteration, if the positions before and after the iteration and the size of the step $\Delta$ are known.

The following analog methods can be used to solve the problem:

a) multi-step optimization method.

Let is $(C_1^0,...,C_l^0)$ is a point of the controllable region corresponding to the initial position of the CD. In it, $F = F^0$.

Option 1. $F^0 \neq 0$:

1) change the position of the $s$-th CD from $N_k$ to $N_{k+1}$, i.e. $\Delta Q_s = Q_s^{N_{k-1}} - Q_s^{N_k}$. Let's calculate the coordinates of the new point $(C_1^{k-1},...,C_l^{k-1})$ and the corresponding value of the target function;

2) move the same CD from the position $N_k$ to $N_{k+1}$, that is $\Delta Q_s = Q_s^{N_{k+1}} - Q_s^{N_k}$, and determine the value of the function $F_s^{k+1}$ at the newly obtained point $(C_1^{k+1},...,C_l^{k+1})$;

3) choose $F_s^{k'} = \min\{F_s^{k+1}, F_s^{k-1}\}$:

- if $F^0 > F_s^{k'}$ – we take $F^0 = F_s^{k'}$ and repeat the operations of p. 1–3;

- if $F^0 \leq F_s^{k'}$ – reduction of the value of the target functional by this CD is impossible. It is necessary to select the next CD and repeat the operations of p. 1–3, etc. until the list of CD used to solve the problem is exhausted.

- let's return again to the $s$-th CD and repeat the entire procedure of minimizing the objective functional from the beginning. If, during a repeated sequential search of all CD, none of them will reduce the value of the goal's functional, the first stage of solving the task is completed; the point obtained on the phase plane ($C_{1ul}$,..., $C_{lul}$) and will correspond to the optimal distribution of air in the MVN at the given mode of operation of the MF.

The second stage of solving the problem is based on changing the operating mode of the MF, if its capabilities are not completely exhausted. In this case, having increased the performance of the MF by $\Delta Q_v$, we determine the new values of $Q(i,j)$ in the controlled workings of the MVN, and taking into account the limitations, we calculate the new value of $F$. If $F\neq 0$, we increase the performance of the MF again, etc. until the moment when $F=0$.

Option 2. $F_0=0$, and to solve the problem it is only necessary to ensure that constraint 6 is fulfilled.

Let's conditionally change the mode of operation of the MF in such a way that the total air consumption decreases by $\Delta Q_v$ and, taking into account (6), we find the new value $F=F'$. If $F'=0$ – it is necessary to repeat the previous actions, obtain $F''$, etc.

Let $F'\neq 0$. In this case, it is necessary to try to finally solve the problem due to the optimal redistribution of air in the mine workings (option 1). If this fails, the MF is put in its previous position and the task is considered solved.

Therefore, in the process of performing the task, it is necessary to determine the mode of operation of the MF after the next movement of the CD, i.e. find a suitable point on the phase plane, and check whether it is in the region of stable and economic operation of the MF. In the case of going beyond the border of the permissible area (3), the movement of the CD cannot be carried out, even if it leads to a significant decrease in the value of the functional $F$;

b) one-step optimization method. In the multi-step optimization method, if during the movement of the $s$-th CD, a decrease in the value of the functional $F$ was achieved, then the next optimization step was produced by the same $s$-th CD. When using the one-step optimization method, it is necessary to move not to the $s$-th, but to the $s$+1st CD, if it leads to a decrease in the value of the functional $F$. Otherwise, it is necessary to move to the $s$+2nd CD, etc. The minimization continues until the successive iteration of the CD allows to minimize the functional $F$;

c) method of extreme coordinate optimization.

Let there be an initial point where $F=F^0$.

Option 3. The state of the controlled object is such that $F^0>0$.

1) change the position of the $s$-th CD from $N_k$ to $N_{k-1}$, which corresponds to $\Delta Q_s = Q_s^{N_{k-1}} - Q_s^{N_k}$, and calculate the value $F_s^{k-1}$ at the obtained point of the controllability area;

2) move the same CD from position $N_k$ to $N_{k+1}$ and calculate the value $F_s^{k+1}$ at the newly obtained point $(C_1^{k+1},...,C_l^{k+1})$;

3) define $F_s^{k'} = \min\{F_s^{k+1}, F_s^{k-1}\}$;

4) repeat the sequence of operations of p.p. 1–3 for $s$+1, $s$+2 and the rest of the CD;

5) from the obtained set of values $\{F_s^{k'}\}$, $s$=1, 2,..., select $F_s^{k''} = \min\{F_s^{k'}\}$ and compare $F_s^{k''}$ with $F^0$. If $F^0 \le F_s^{k''}$ – minimization of $F$ only due to the redistribution of air in the MVN is impossible, and it is necessary to change the operating mode of the MF. If $F^0 > F_s^{k''} \Rightarrow F^0 = F_s^{k''}$, and we repeat the sequence of operations p.p. 1–5.

The process is repeated until $F^0 \le F_s^{\bar{k}}$, or $F_s^{\bar{k}} = 0$, i.e. the task is completely solved.

The second stage of solving the problem is necessary if the value of $F \neq 0$, and the MF reserves are not completely exhausted. In this case, we will increase the performance of the MF by $\Delta Q_v$ and calculate the new value of $F$. If it is not equal to zero, the first stage of solving the optimization problem is carried out again. If $F$=0, the task is completely solved.

Option 4 for the method of extreme coordinate-wise optimization is similar to option 2 in the method of multi-step optimization [7,8].

## 3. Discussion

The considered methods ensure a monotonous reduction of the values of the functional $F$ to the extremum, guaranteeing the convergence of the search processes. The analysis shows that the method of extreme coordinate optimization is the best, the efficiency of solving the problem is 1.5–3 times higher than that of the other considered methods.

It should be noted that the developed methods of solving the task of managing air distribution in the MVN during the elimination of an exogenous fire will be most effective only when they are used as part of an automated system in operational mode of operation and providing feedback between the device for generating the effects of controllers and CD. Otherwise, the delay of the signal to change the position of the CD can lead to an undesirable redistribution of gas and air flows in the MVN and a decrease in control efficiency. In addition, in the complex solution of the tasks of managing the progress of liquidation of an emergency situation, it is necessary to additionally solve the issue of the ratio of air distribution management and emergency evacuation of miners, giving preference to the management of those CD-s that are not located on the paths of people's movement, in order to avoid disruption of this process [9,10].

## 4. Conclusions

Reducing the emergency and aerological risks of choosing emergency modes with the use of emergency protection means is a promising direction of mining practice, since, firstly, it reduces the risk of too sharp regulation of ventilation flows by general mine regulation, and secondly, the inertia of ventilation flows and the size of emergency and gassed zones are decreasing.

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## ЗНИЖЕННЯ РИЗИКУ ВИБОРУ АВАРІЙНОГО ВЕНТИЛЯЦІЙНОГО РЕЖИМУ ШЛЯХОМ МІСЦЕВОГО КЕРУВАННЯ ВЕНТИЛЯЦІЙНИМИ ПОТОКАМИ

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**Анотація.** Реалізація заходів щодо організації аварійного провітрювання шахти пов'язана, як і в інших випадках функціонування підприємств підвищеної небезпеки, з різними видами ризиків. Зокрема, це стосується аварійного ризику, який виникає при необхідності аварійної евакуації людей з виробок шахти, загазованої продуктами пожежі (тобто ризику їх отруєння або ураження за рахунок теплового фактора) та аварійного ризику, який провокується неправильним вибором та здійсненням аварійного вентиляційного режиму. Обидва види ризиків вимагають для зниження використання засобів вентиляційного впливу – вентиляторів головного і місцевого провітрювання. Повинно бути також передбачено використання різноманітних пасивних регулюючих пристроїв. Основним результатом методологічного підходу, що використовується нині, є вибір аварійного вентиляційного режиму, що максимально обмежує зону загазування шахтної вентиляційної мережі газоподібними продуктами горіння. Критерієм ефективності аварійної евакуації гірників при цьому має бути максимальне використання незагазованих виробок, чим і досягається мета управління вентиляцією при аваріях.

Пропонований функціонал управління, що характеризує ступінь ризику розподілу пожежних газів виробками шахти, є середньоквадратичним відхиленням концентрації пожежних газів у контрольованих гілках мережі від необхідного рівня стабілізації. Для двох регулюючих пристроїв і двох регульованих ділянок він є частиною тривимірного конуса, а область керованості обмежена двома гіперболами. Аналогічно виглядає постановка завдання при збільшенні розмірності базису регулюючих приладів. Сформульовано обмеження на постановку завдання, і зроблено висновок щодо можливості застосування для її вирішення аналог-методів динамічного програмування. Як такі розглянуті метод багатокрокової оптимізації, метод однокрокової оптимізації та метод екстремальної покоординатної оптимізації (останній – найефективніший). Найбільшої ефективності їх використання буде досягнуто при впровадженні автоматизованої системи управління провітрюванням, що забезпечує зворотний зв'язок засобів регулювання та регулюючих пристроїв.

**Ключові слова:** аварійний ризик, аерологічний ризик, функціонал управління, регулюючі пристрої, екзогенна пожежа.