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Automated ventilation control in mines. Challenges, state of the art, areas for improvement

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Abstract. The article is divided into three main parts. The first part provides an overview of the existing literature on theoretical methods for calculating the optimal air distribution in mines according to the criteria of energy efficiency and providing all sections of mines with the required amount of air. It is shown that by the current moment there are many different formulations of the problem of searching the optimal air distribution, many different approaches and methods for optimizing air distribution have been developed. The case of a single (main) fan is most fully investigated, while for many fans a number of issues still remain unresolved.

The second part is devoted to the review of existing methods and examples of the automated mine ventilation control systems implementation in Russia and abroad. Two of the most well-known concepts for the development of such systems are automated ventilation control systems (AVCS) in Russia and the CIS countries and Ventilation on demand (VOD) abroad. The main strategies of ventilation management in the framework of the AVCS and VOD concepts are described and also the key differences between them are shown. One of the key differences between AVCS and VOD today is the automatic determination of the operation parameters of fan units and ventilation doors using the optimal control algorithm, which is an integral part of the AVCS.

The third part of the article describes the optimal control algorithm developed by the team of the Mining Institute of the Ural Branch of the Russian Academy of Sciences with the participation of the authors of the article. In this algorithm, the search for optimal air distribution is carried out by the system in a fully automated mode in real time using algorithms programmed into the microcontrollers of fans and ventilation doors. Minimization of energy consumption is achieved due to the most efficient selection of the fan speed and the rate of ventilation doors opening and also due to the air distribution shift control and the partial air recirculation systems introduction.

It is noted that currently the available literature poorly covers the issue related to emergency operation modes ventilation systems of mines and also with the adaptation of automated control systems to different mining methods. According to the authors, further development of automated ventilation control systems should be carried out, in particular, in these two areas.

***Key words*:** mine ventilation; air distribution; optimal control; automated control; ventilation on demand

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Introduction. The main task of any underground ventilation system, according to [39], is to provide all working areas (or all consumers) with air in sufficient quantity and quality to dilute pollutants to safe concentrations. At first sight, this task seems easy to solve. However, as mine ventilation networks become deeper and branched, the air temperature in distant working areas increases, the process of supplying fresh air to the end user becomes more complicated, and the volume of gases released during mining operations increases. As a result, the implementation of the main task of the ventilation system becomes more complicated [42].

Providing all work areas with the necessary amount of fresh air is not the only task of ventilation. The energy efficiency is increasingly required for mine ventilation systems [17]: total electricity consumption should be minimal. This requirement is logical from the point of the lean production concept [44]. The main principle of lean production is to reduce all actions that do not add product value, throughout its life cycle. According to various estimates, the share of total electricity costs associated with ventilation and air handling systems in mines varies in the range of 30-70 % [18, 29, 30, 42].

The two mentioned tasks of ventilation systems are based on two opposing criteria: when solving the problem of providing air, it means increasing the air flow in the ventilation network, and the second task is aimed at reducing it as much as possible. A rational solution to both problems of ventilation systems, which allows determining the optimal distribution of air in a ventilation network according to the criteria of energy efficiency and dilution of pollutants, is possible only with the use of methods of optimal control theory. And the implementation of the optimal air flows distribution in practice in the conditions of dynamically changing mine ventilation networks is possible only with the use of automatic ventilation control [8].

This article is devoted to the analysis of the existing literature both on the optimal control methods of air distribution in mines, and on the implementation of ventilation control systems in practice. The analysis presented in the article is important for understanding the state of the art and directions of further development of theoretical and technical facilities of mine ventilation control. The article also describes in detail the algorithm for optimal control of ventilation devices in mines.

Methods and algorithms for optimal air distribution control. When developing and implementing ventilation control systems in mines, first of all, it is necessary to determine the optimal ventilation mode of the mine, to which the control system in consideration will strive. The optimal ventilation mode, as a rule, means such a mode in which the following conditions are met:

• minimum power consumed by all fans in the ventilation network of a mine,

$$N = \sum_{i=1}^{n} \frac{H_i Q_i}{\eta_i} \to \min; \tag{1}$$

• provision of all working areas with the required amount of air

$$Q_j \ge Q_j^*, \quad j = 1, .., m, \tag{2}$$

where i and j are indices of fans and working areas respectively; n – number of fans; m – number of working areas; Q – air flow, m^3/s; H – fan pressure, Pa; η – the efficiency of the fan system; Q^* – air flow in the working area required for dilution of contaminants and ensure a comfortable microclimate, m^3/s.

As optimization parameters for minimizing the functional (1) under conditions (2), as a rule, the aerodynamic drags of mine workings and fan pressures are used [15]. The change in the aerodynamic drag of mine workings can occur due to changes in the parameters of ventilation structures located in them, and the change in the fan pressures – due to changes in the speed of the impellers, the rotation angles of the impeller blades or guide vanes [8, 11].

The problem of optimal ventilation control in mines has been formulated a long time ago. For the first time, this kind of problems are considered in the USSR in monographs [1, 11, 19]. In the monograph [11] there was proposed a global criterion for an optimal ventilation of the mine, taking into account the capital cost of deploying a control system ventilation and also, apart from conditions (2), additional conditions of optimality are considered: the concentration of harmful pollutants should not exceed the corresponding maximum permissible values, i.e., apart from the condition (2), a condition of the form is written:

$$C_j \le C_j^*, \quad j = 1, .., m, \tag{3}$$

where C_j^* is the maximum permissible concentration of harmful pollutants and C_j is the actual concentration in the atmosphere of j-th mine working.

From the point of view of theoretical calculations, conditions (2) and (3) are most often equivalent, since the preliminary calculation of the required air flow Q^* is made based on the maximum permissible concentrations of harmful pollutants in the atmosphere of mine workings. However, when deploying algorithms for optimal air distribution control in mines, conditions (2) and (3) cease to be equivalent, since their verification is carried out experimentally using sensors that measure fundamentally different physical quantities.

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Also, in the monograph [11] it is first described that when the optimal ventilation mode of a mine is reached, the ventilation structure of the most hard-to-ventilate air path must have zero aerodynamic drag.

In the monograph [19], a criterion for optimal ventilation network control is formulated, a method for optimal ventilation network control based on linearization with subsequent application of the simplex method is proposed, and the problem of finding optimal schemes of ventilation networks is considered for the first time. In the monograph [1], the problem of optimal ventilation control is also solved using linear programming methods. In this monograph, a particular problem of optimal control at a given air flow in all workings of the ventilation network is considered. According to the authors of the sources [8, 22], linear programming methods have slow convergence and often lead to solution divergence, since in general the problem under consideration is non-convex.

Subsequently, the ideas of optimal control were developed in the monograph [15], which formulated a generalized problem of optimal ventilation control in mines, which allows to take into account various limiting conditions and optimum criteria. Various algorithms for solving the optimal control problem based on the Newton's method, the iteration method, and the steepest descent method are considered. These methods are generalized and combined into a single flexible algorithm for finding the optimal ventilation mode. The idea of this algorithm is to additively take into account various conditions of the problem and extremality conditions in the formation of the Hessian matrix.

In foreign literature, the active study of the optimal ventilation control problem in mines began later – in the late 80 – early 90-s of the last century. At this time in the works [24, 26, 31, 32, 34, 43, 45] various mathematical methods and approaches to minimize the energy consumption of mine ventilation networks were described. These studies also primarily consider linear programming methods (network simplex method). In addition to this method, the article [45] considers the critical path method (CPM), based on the selection of the greatest aerodynamic drag path in the ventilation network.

In foreign studies, under the task of optimizing air distribution in the mine ventilation network, as a rule, a more general problem is considered. As part of this task, it is necessary to identify the number, location and operation mode of fans and regulators [22], while in the Russian literature it is usually assumed that negative regulators (doors, stoppings etc.) are located in a fixed set of mine workings, where air flows are known (given) [1, 5, 8]. For example, in [24, 32], the locations of positive regulators (fans) and negative regulators in the ventilation network are determined. In [26], the problem of selecting optimal locations for only positive regulators is considered.

Current studies on this issue are aimed at developing new numerical methods for optimizing air distribution in mine ventilation networks of arbitrary topology. In [27], the problem of optimal mine ventilation is solved by sequentially solving quadratic programming problems approximating the original optimization problem. In [37], a method of asymptotic calculations of air flows for determining the positions and drags of negative regulators in the ventilation network is proposed. In this method, the set of workings with regulators is determined based on the proposed matrix of oriented paths. In [4, 13, 21, 38], genetic algorithms are used to solve the problem of optimal placement of negative regulators and subsequent distribution of air flows in the mine ventilation network. In [6], an optimization algorithm is proposed that performs a preliminary "over-speeding" of the main fan to such an impeller speed at which the conditions (2) will be met for the first time. Then there is an iterative speed reduction, accompanied by a redistribution of air flows in the ventilation network through negative regulators. The redistribution of air flows is performed by solving the optimization problem using a modified multidimensional Newton's method.

Practically none of the existing studies of optimal ventilation modes of mines proves that the found solution is a global optimum. The exception is [8, 11] research. In these works, similar algorithms are proposed for finding the optimal ventilation mode by controlling the parameters of negative and positive regulators. For the case of a single main fan, it is strictly proved that the obtained solution corresponds to the optimum (1)-(2).

A separate class of methods for optimal air flows distribution is the solution of inverse air distribution problems, first applied to the problems of mine ventilation in the works [5, 10]. The idea is that the system of equations (Kirchhoff's first and second laws), redefined due to additional conditions of the form (2), is supplemented by new unknowns – fan pressures [5] or additional drags [10] in branches with a given air flow Q^*.

Automated air distribution control systems. The automated air distribution control system in mines is a more extensive concept in comparison with algorithms for optimal air distribution control, since it also includes technical facilities that collect information about the atmosphere parameters of the mine workings, transmits information to servers and computing units, stores information and displays it graphically at the controller's workplace. This list should also include technical facilities and algorithms of microcontrollers that allow changing the parameters of positive and negative regulators in real time (for example, the impellers speed of fans, the rotation angles of the ventilation doors flaps).

The first work is the monograph [11] in which the theoretical foundations of the construction of automated air distribution control systems in mine ventilation networks are sufficiently fully described. It highlights three main operations performed by such systems (information collection, information processing, and decision realization), and provides a classification of the various methods to perform these operations.

Classification of methods for performing basic operations of automated air distribution control systems:

1. Information collection:

a) manually;

b) automatically (using stationary sensors).

2. Information processing:

a) manually without the use of special computing devices;

b) with the use of special computing devices (on a computer model of the ventilation network); the initial data is entered manually;

c) automatically using a computer model of the ventilation network, coupled with the information collection system;

d) automatically with the help of microcontroller algorithms that are interfaced with both the information collection system and the ventilation device controllers.

3. Decisions realization:

a) manually on site;

b) manually remotely (from the control room);

c) automatically.

Information processing refers to the control error determination by air flows and (or) gas concentrations and the calculation of the necessary control actions for positive and negative regulators. The decisions realization is understood as a direct change in the operating modes of positive and negative regulators.

The situation of fully manual control of the mine ventilation corresponds to the "a-a-a" mode, while fully automatic control corresponds to the "c-d-c" mode. The remaining modes are automated control, where some part of the operations is performed by a person.

In the monograph [11], a classification of approaches to automated ventilation control is carried out. Two approaches are highlighted, the key difference between which lies in the method of calculating the optimal parameters of positive and negative regulators – by solving the problem of optimal air distribution control or by using methods of the automatic control theory.

In the first approach, it is assumed that the topology and geometric parameters of the workings system are known, there is a computer model of the ventilation network, on which the specialist automatically performs a numerical calculation of the optimal air distribution in the mine and receives the required parameters of ventilation devices (fan effectiveness, drag of ventilation structures). In the second approach, the topology and geometric parameters of the ventilation network may be unknown, and the control actions on the regulators of ventilation devices are determined by microcontrollers, based on their current values and deviations of the actual values of the controlled values (air flows, gas concentrations) from the required and (or) critical values.

Also, in the monograph [11], the classification of ventilation networks into easily controlled and hard-to-control ones is proposed. The criterion for classifying a ventilation network as hard-to-control is as follows: if among the elementary cycles of the complete graph of the ventilation network there is at least one cycle that does not contain any ventilation control objects and includes two or more fan units. In future, a similar classification was given in [10], where complex ventilation systems are understood as ventilation systems that have two or more fans with different zones of aerodynamic influence.

In the monograph [15], the term automated ventilation control systems (AVCS) was introduced, which later found wide application in the Russian scientific literature [3, 8, 7, 14]. The generalized structure of AVCS of mines is given, including elements responsible for the following main functions:

- collecting information about the state of the mine atmosphere and technical facilities;
- ventilation state analysis and calculation of control actions for technical facilities;
- display of information about the ventilation state and operability of technical facilities;
- testing of control actions by technical facilities.

This classification is similar to the classification of basic operations proposed in the monograph [11]. The main difference is that the information processing operation in the monograph [15] is divided into two functions: the first one performs all internal calculations of ventilation parameters and assesses the state of the system, and the second one is intended for communication with the operator, providing basic information about the state of the ventilation system and technical facilities.

To determine the optimal values of the regulators, the authors solve the problem of optimal air distribution control on a computer. The output of each regulator in the optimal operation mode is performed by sending a message to a drive of control actions according to the proportional-integral control law. In the monograph [15], it is indicated that the calculation of control actions can be performed in various ways: by the coefficients of air supply of working areas, by the deviation of air flows from the required value, by means of more complex indicators of safe ventilation, taking into account gas concentrations, air temperatures, etc. The most flexible system, according to the authors, is a system that combines all possible variants of control algorithms. However, as noted in the monograph [11], it is important to take into account the different inertia of aerodynamic and gas-dynamic processes. The different inertia is mainly connected to the fact that for aerodynamic processes the velocity of disturbance transfer is equal to the sound speed in the air, while for gas – dynamic processes it is equal to the average air movement speed in the mine development.

In the last decade, the principle of ventilation on demand (VOD) has been actively developing abroad. This term was first mentioned in [30, 41]. According to the definition given in [40], VOD is such a ventilation system organization in which fresh air is directed only to those mine areas where it is required, in the amount necessary for mining operations and maintaining comfortable working conditions during a given period of time (for example, the time period of the mining shift). Thus, the concept of VOD is to supply fresh air mainly to those working areas in which mining operations are carried out, while in the remaining part of the mine, air flow should be minimized [42]. Due to this minimization of air flow, electricity savings are achieved.

In [42], three global stages of VOD are highlighted:
• remote control;
• manual or automated control based on a list of predesigned modes;
• fully dynamic automated control system (the air flow is constantly monitored and regulated based on knowledge of the equipment location and the ongoing mining activities online).

In [40], an alternative, more differentiated classification is presented, including five VOD strategies:
1) remote control;
2) time of day scheduling (based on a list of predesigned modes);
3) event-based control;
4) tagging;
5) environment.

The first strategy, as the name implies, allows manual (remote) control or adjustment of operating points for various technical facilities of the ventilation system.

The second one implements the principle of shift regulation of air flow in the mine – the launch of various pre-calculated setpoints Q^* for each of the positive and negative regulators in accordance with a certain schedule of mining operations in different mines.

The third strategy involves automatically launching the prescribed actions in response to certain events that have occurred and registered by the sensor system (exceeding the maximum permissible concentrations of gases, smoke pollution from workings, etc.). This strategy is necessary for automating emergency ventilation.

The fourth strategy is the positioning of miners and equipment. It requires the implementation of a location sensors system and associated software to visualize the actual coordinates of miners and equipment on the mine ventilation network. The calculation of the required amount of air flow and its delivery to each working mine area in this case is determined based on the actual number of personnel and the number of each type of equipment units in this working area.

The fifth control strategy is related to the complex provision of comfortable working conditions in the work area for such factors as gas, dust, the content of solid particle matters from diesel engines (DPM), the perceived temperature, etc. Automatic control in this case should be based on a comprehensive set about environmental data read from the appropriate sensors in real time. The key difference between the fifth strategy and the previous ones is the control of ventilation devices according to the atmosphere parameters measured "directly", without using a database with the required amounts of fresh air calculated in advance according to the method adopted at the mine.

If the article [42] implies a consistent improvement of the mine ventilation system along the way from the first stage to the third, then there is no such restriction in the classification of the article [40]: the improvement of the mine ventilation system can occur through the implementation of various strategies from this list in any order. Next, the classification of the article will be used [40].

If we compare the classification of ventilation control systems given in the table of the monograph [11] and the classification of VOD strategies, it can be concluded that VOD corresponds to ventilation control systems with sets of methods "b-b-b" and higher. At the same time, the fourth VOD strategy (positioning) in the Russian literature, as a rule, is considered separately – in relation to safety issues and notification of various emergency situations [2, 16]. In this sense, it can be assumed that the fourth strategy in the Russian literature is combined with the third.

The most cost-effective set of ventilation management strategies for each mine is determined individually, taking into account the unique characteristics of each mine [11, 40].

The foreign literature presents many studies on the VOD implementation at various mines [23, 25, 20], and studies on the economic effectiveness justification of VOD strategies in terms of specific mines in advance of implementation [28, 29, 40]. Most often, cases of only the second VOD strategy implementation – automated shift ventilation control – are described [20, 25].

In the last decade, Russian and CIS mining enterprises have been actively implementing the ventilation management strategy proposed in [7, 8]. This strategy is analogous to VOD, but has two key differences:

1) minimization of energy consumption is achieved not only through air distribution shift control, but also through the implementation of partial air reuse (controlled recirculation) systems;

2) the search for optimal air distribution is carried out by the system in a fully automated mode using algorithms programmed into the microcontrollers of fans and ventilation doors.

The first difference occurs only for ore deposits, since the use of recirculating ventilation in coal mines is prohibited by safety regulations. According to the authors of the article [9], the reduction of energy consumption with the AVCS implementation with partial air reuse at the potash mines of JSC Belaruskali and PJSC Uralkali can reach 70 %.

The second difference becomes possible due to the algorithm developed in [8] for controlling ventilation devices for the case of ventilation networks of random topology with one main fan in real time.

Algorithm for optimal control of AVCS ventilation devices. The control algorithm is based on a set of general rules that are formulated for automatic ventilation doors (AVD) and the main fan (MF).

Rules for controlling each AVD:

• An AVD will be opened when either it itself or at least one of the consecutive AVDs related with it has insufficient air flow;

• An AVD will be closed if there is insufficient air flow in at least one parallel AVD connected to it.

If all AVDs that are consecutive to a given AVD have an excess air flow, and at the same time there is also an excess air flow in this AVD, then this AVD should be closed.

MF management rules:

• if there are working areas in which the air flow is less than the declared one, then the MF increases the rotation speed;

• if all AVDs are closed, the MF reduces the rotation speed until at least one AVD is fully open;

• if there is excess air flow in all working areas, the MF reduces the rotation speed.

Insufficient air flow is defined as a value $\Delta Q_j^{\,-} = \max\left(0, Q_j^* - Q_j\right)$. Excess air flow is defined as a value $\Delta Q_j^{\,+} = \max\left(0, Q_j - Q_j^*\right)$, where j is the number of the working area.

This algorithm is quite simple and can be programmed into a microcontroller that directly controls ventilation devices (doors, fans). The algorithm does not require network models of air distribution and information about the topology of the ventilation network.

Based on the formulated control rules for each AVD, the formula for the AVD control pulses is written:

$$F_i = I_{AVD}\left(\Delta Q_i^+ - \sum_j \Delta Q_j^+ + \sum_{k \neq i} \Delta Q_k^- + \Delta Q_i^- \lambda\right), \tag{4}$$

where I_{AVD} is the intensity of AVD control, determined during start and setup of the AVCS system; λ is a logical function:

$$\lambda = \begin{cases} 1, & \text{all neighboring AVDs have an excess air flow} \\ 0, & \text{not all neighboring AVDs have an excess air flow} \end{cases}. \tag{5}$$

Based on the formulated control rules for MF, the formula for MF control pulses is written:

$$G = I_{MF}\left(\max_i\left(\Delta Q_i^+\right) - \min_i\left(\Delta Q_i^-\right)\right) + A_{MF}\min_i\left(\varphi_i\right), \quad (6)$$

where I_{MF} is the intensity of MF control, A_{MF} is the intensity of coupling of MF and AVD, φ_i – rotation angle of the AVD blinds N i.

Further development of this algorithm is described in [12, 33, 35], which also presents examples of AVCS practical implementation based on the optimal control algorithm described above. In [33], instead of functions (4)-(6), dependencies obtained from a regression model based on neural networks are used. The control system algorithm is modified to use a set of historical data accumulated during the control system operation. Thus, for the first time, an attempt is made to move from an automated to an intellectualized ventilation control system. The paper [12] describes the experience of implementing automated ventilation control systems at the potash mines of JSC Belaruskali (mines 3-RU and 4-RU). For the conditions of the 4-RU mine, the strategy of shift automated ventilation control was implemented in the conditions of several main fans. A unique example of the AVCS implementation at the 4-RU mine is described, the ventilation network of which, according to the classification of work [11], is hard to control.

Conclusion. An analysis of the literature on methods and algorithms for optimal air distribution control has shown that many different approaches and methods for optimizing air distribution have been developed to date, using linear programming, genetic algorithms, the Newton's method and its various modifications, methods for solving inverse problems of air distribution, methods of automatic control theory, etc. The problem of finding the optimal air distribution for one main fan is most fully investigated, while for many fan units a number of issues remain unresolved. In particular, there is no strict proof of the optimality of the obtained solutions for a variety of fns.

To date, a large volume of literature has been accumulated on the ventilation control systems development. There are two global concepts for the development of such systems – AVCS in Russia and the CIS countries and Ventilation on demand (VOD) – abroad. This paper shows the key differences between AVCS and VOD. It is also noted that while in the foreign literature such management strategies as positioning and responding to possible events are most often divided among themselves, in Russia and the CIS countries they are considered as a single strategy for improving safety in the automation of ventilation systems.

In the existing literature, there are few examples of practical implementation of AVCS and VOD, and the described examples are usually very limited. First of all, this applies to examples of VOD implementation. At the same time, with regard to the AVCS implementation, the most advanced system to date is the automated ventilation control system at the 4-RU mine of JSC Belaruskali, which implements automatic shift control and allows to determine the parameters of several main fans and automatic ventilation doors in real time.

Implemented and described in the literature options for AVCS and VOD are given for a limited number of options for mine development. The proposed solutions are not adapted for arbitrary options for development systems of deposits. At the same time, multi-level mining methods with through-flow ventilation systems are widely used, for which the problems of air distribution management and control are not solved.

In the literature, little attention is paid to emergency modes of automated ventilation systems operation. The problem is rather the imperfection of existing methods of processing information about the mine atmosphere state. At the same time, taking into account the modern development of the instrument base, there is no problem with obtaining a sufficient amount of measurement data. Perhaps, in this situation, the most effective methods of analysis and decision-making in future will be the methods of intelligent ventilation management.

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