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DEVELOPMENT OF AUTOMATED MINE VENTILATION CONTROL SYSTEMS FOR BELARUSIAN POTASH MINES

In recent decades, two different approaches to mine ventilation control have been developed: ventilation on demand (VOD) and automatic ventilation control (AVC) systems. The latter was primarily developed in Russia and the CIS countries. This paper presents a comparative analysis of these two approaches; it was concluded that the approaches have much in common. The only significant difference between them is the optimal control algorithm used in automatic ventilation control systems. The paper describes in greater detail the algorithm for optimal control of ventilation devices that was developed at the scientific school of the Perm Mining Institute with the direct participation of the authors. One feature of the algorithm is that the search for optimal airflow distribution in the mine is performed by the system in a fully automated mode. The algorithm does not require information about the actual topology of the mine and target airflows for the fans. It can be easily programmed into microcontrollers of main fans and ventilation doors. Based on this algorithm, an automated ventilation control system was developed, which minimizes energy consumption through three strategies: automated search for optimal air distribution, dynamic air distribution control depending on the type of shift, and controlled air recirculation systems. Two examples of the implementation of an automated ventilation control system in potash mines in Belarus are presented. A significant reduction in the energy consumption for main fans' operation obtained for both potash mines.

Keywords: Mine ventilation, ventilation on demand, automated ventilation control, energy efficiency, main fan, ventilation door, potash mines

1. Introduction

The current state of mining and increased mineral production has led to the expansion of mine ventilation networks and, consequently, to the complication and worsening of mine ventilation. Therefore, air distribution in numerous directions and panels has deteriorated, resulting in the

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unreasonably low total efficiency of main fans, high energy consumption, and the impossibility of providing all mine working areas with a sufficient amount of fresh air. Air distribution control in the ventilation networks of large mines is a significant challenge. An efficient solution to this problem, under strict mine safety standards, is unattainable without automated ventilation control systems, mathematical forecasting methods, and the optimization of air distribution in extended ventilation networks (Kazakov & Shalimov, 2012).

There are currently two main problem-solving approaches available to provide efficient air distribution control in the ventilation networks of large mines:

1. Automated ventilation control (AVC) systems.
2. Ventilation control systems based on the ventilation on demand (VOD) principle.

It should be noted that this classification does not take into account theoretical methods which consist of simulating airflow distribution in ventilation networks and solving the optimal control problem (Barnes, 1989; Jaques, 1991; Huang & Wang, 1993; Lowndes, 2005; Li et al., 2018).

The ventilation control system is a broader concept than the optimal control problem. It also includes the technical means to obtain the measurement data from the mine, specify control actions on ventilation devices in the mine, and visualize the actual state of the workplace's ventilation system from the mine office. Nevertheless, ventilation control systems are based on two principles formulated for the first time in theoretical works on the optimal regulation of air distribution in mine ventilation (Tsoy & Rogov, 1968). According to these principles, it is necessary to determine such operation modes of fans (impeller rotation frequency and vanes installation angle) and such positions of airflow regulators (turning angle of automatic ventilation doors) as are suitable for the following conditions:

1. The actual airflow Q_i in each i-th working area is not less than the corresponding airflow lower limit Q_i^* providing sufficient ventilation of the working area

$$Q_i \geq Q_i^*, \; i = 1, \ldots, N \tag{1}$$

2. The total energy consumption of fans has a minimum value

$$\sum_j N_j \to \min \tag{2}$$

where N_j is the power consumption of the j-th fan.

This formulation is the most common (Kruglov & Semin, 2013), but it is not the only one possible; in some published works (Abramov et al., 1978; Acuna & Lowndes, 2014), this definition is expanded to determine the optimal locations of the ventilation doors and stoppings. In the monograph (Mester & Zasukhin, 1974), a global criterion for optimal ventilation mode is presented, taking into account the capital costs of installing the hardware components of the AVC system (sensors, controllers, data communications network, database, etc.). In addition to principles (1)-(2), another optimality principle is considered:

3. The concentration of harmful impurities in working areas should not exceed the corresponding maximum permissible values:

$$C_i \leq C_i^*, \; i = 1, \ldots, N \tag{3}$$

where C_i^* is the maximum permissible concentration of harmful impurities in the i-th working area (although most often this value is the same for all areas).

From the perspective of theoretical calculations, conditions (1) and (3) are equivalent, since the preliminary calculation of the required amount of air Q_i^* in each working area is usually made based on the time-averaged measured concentrations $\langle C_i \rangle$ and maximum permissible concentrations C_i^* of harmful impurities in the atmosphere of the working areas. However, in the practical case, conditions (1) and (3) cease to be equivalent, since they are controlled experimentally using sensors, which measure principally different physical quantities. Harmful impurities are distributed much more heterogeneously, both in time and in mine space. The response time of actual parameters Q_i and C_i to the actions of the control system is also different. Further in this work, we will only discuss principles (1)-(2).

2. Automated ventilation control systems

A monograph by Mester and Zasukhin was the first work to adequately describe the theoretical foundations for constructing ventilation control systems in different types of mines. This monograph identifies three main operations performed by such systems (data collection, processing, and execution), as well as a classification of various methods for performing these operations (see Tab. 1).

TABLE 1

Classification of methods for performing basic operations of ventilation control systems

Operation	Methods and means of performing operations
Data collection	I. Manually. II. Automatically (using stationary sensors).
Data processing	1. Manually, without the use of computer. 2. Manually, using computer (performing simulation on ventilation network models); initial data is entered manually. 3. Automatically, using a simulation model of the ventilation network, coupled with a data collection system. 4. Automatically, with the help of microcontroller algorithms, interfaced with both the data collection system and the ventilation devices.
Execution	A. Manually, in place. B. Manually, remotely. C. Automatically.

The case of fully manual control of mine ventilation system corresponds to mode I-1-A, while fully automatic control corresponds to mode II-4-C. The remaining modes represent partially automated control, wherein some operations are performed by humans.

The monograph (Puchkov & Bahvalov, 1992) introduced the term "automated ventilation control system" and the corresponding Russian abbreviation *SAUP*, which later became widely used in the scientific literature of post-Soviet countries. In this article we will use the abbreviation AVC (automated ventilation control) when we talk about automated ventilation control systems developed in Russia and the CIS countries.

Further development of the AVC concept is described in several works (Kazakov & Shalimov, 2012; Kruglov, 2013; Kruglov & Semin, 2013; Levin & Semin, 2017; Kashnikov & Levin, 2019). Special attention should be paid to the work by Kruglov and Semin in which an algorithm for optimal ventilation control was proposed for the controllers of fans and ventilation doors. The main feature of the algorithm is the possibility to determine the most energy-efficient operational mode for fans and automated ventilation doors without solving the air distribution problem. The minimization of energy consumption is dependent on the general properties of airflow regulators in the energy-efficient mode and does not require an explicit expression of the total fan-power consumption function. The algorithm developed by Kruglov and Semin became an integral part of the AVC system developed at the Perm Mining Institute. A more detailed description of this algorithm is given in the next section of this paper. This paper also provides further development of this algorithm in the case of several main fans.

For non-coal mines, an additional energy-saving strategy arises in Russia and CIS countries concerning the use of controlled recirculation. If the contaminant concentration in the return air is significantly lower compared to the maximum allowable concentration, then the controlled recirculation of return air can be applied in accordance with RF (Russian Federation) Mining Safety Regulations, Belarusian Regulations for Occupational Safety, etc. We mention here the Belarusian regulations because hereinafter we will focus on the use of AVS systems in Belarusian mines.

Since the measured gas concentrations (methane and hydrogen sulphide) in the return air in the potash mines are indeed very small, the controlled recirculation systems can be safely used with a further proviso. From clause no. 201 of the Belarusian Regulations for Occupational Safety, it follows that the automated monitoring of contaminants should be provided for at the junction of fresh and return air where controlled recirculation is to be considered.

Another important aspect of the AVC system is its ability to provide dynamic control of fans and ventilation door parameters for different mine ventilation modes (mining operations, repairing works, emergencies, etc.) and for different numbers of operating mining equipment items. The system recalculates the lower limits of airflow relative to the technique for calculating the required amount of air, on the basis of real-time data reflecting the number of operating equipment items and the number of people in each working area.

Thus, the increased energy efficiency of the mine ventilation system with AVC can be achieved by means of an algorithm for optimal ventilation control, controlled recirculation, and dynamic assignment of lower airflow limits in real time.

AVC systems are currently used at mines 1-RU, 3-RU, 4-RU, the Berezovskya and Krasnoslobodskaya mines of the Belaruskali company, and at mines BKPRU-2 and BKPRU-4 of the Uralkali company (Kruglov et al., 2013; Kruglov & Semin, 2013). It implements principles (1)-(2) by means of on-line control of the impeller rotation frequencies of main fans and the opening angles of ventilation doors. In cooperation with the NPO Mikont and AeroSfera companies, the Perm Mining Institute has developed source documents for designing an AVC system for these mines.

3. Ventilation on demand

Over the two last decades, the ventilation-on-demand (VOD) principle has been actively developed around the world. This term was first mentioned in (Hardcastle et al., 1998; Hardcastle et al., 1999). In the early 2000s, the VOD principle was developed and improved in response to increasing energy usage and costs. According to the definition given in (Tran-Valade & Allen, 2013), VOD is the ability to direct air in an underground mine to the area that requires it, in the quantity needed for the local activities and ambient conditions at the time. In other words, it is the ability to provide the required air volume to where it is needed, and only when it is needed.

Thus, the idea of VOD is to save electricity by reducing the supply of fresh air to those working areas in which mining operations are not being conducted at the considered time period.

In (Wallace et al., 2015), three global stages of VOD are distinguished:

1. A system that is remotely controlled.
2. A system that is controlled by a list of predesigned modes or set points of operation.
3. A fully dynamic control system where airflow is continually controlled and balanced based on knowledge of equipment location and mining activities.

In (Tran-Valade and Allen, 2013), an alternative, more differentiated classification is presented, including five VOD strategies:

1. User control,
2. Time of day scheduling,
3. Event-based,
4. Tagging,
5. Environmental.

A more detailed description of each of these five strategies can be found in the work (Tran-Valade and Allen, 2013) or in the work (Acuna et al., 2016). The most cost-effective set of ventilation control strategies for each mine is determined individually, taking into account the unique characteristics of each mine (Mester & Zasukhin, 1974; Tran-Valade & Allen, 2013).

If (Wallace et al., 2015) 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 (Tran-Valade & Allen, 2013); the mine ventilation system can be improved by implementing various strategies from this list in an almost arbitrary sequence.

The ventilation-on-demand (VOD) principle has been further developed by other researchers (Hardcastle & Kocsis, 2002; Hardcastle et al., 2006; Tuck et al., 2006; Bartsch et al., 2010). The literature contains many studies on the implementation of VOD strategies in North American mines (Acuna & Allen, 2017; Brokering et al., 2017; Nel et al., 2019), as well as many studies on the rationale for the cost-effectiveness of VOD strategies in specific mines, as well as mines prior to their immediate implementation (Tran-Valade & Allen, 2013; Chatterjee et al., 2014; De Vilhena Costa & Margarida da Silva, 2019). Most often, the literature describes cases of introducing only the second VOD strategy: control by a list of predesigned ventilation modes (Tuck et al., 2006; Brokering et al., 2017; Nel et al., 2019).

The advantages of using the VOD principle (Bartsch et al., 2010) are:

1. Variable fan impeller rotation frequencies to provide required airflows in working areas with minimal energy consumption.
2. Variable fan-vane angles to guarantee maximal total efficiency.
3. Placement of automated air regulators (ventilation doors) for each stopping area.
4. Global mine monitoring system, including airflow and gas sensors for each stopping area.
5. Separate ventilation department within the mine.

4. Comparison of VOD and AVC approaches

The global objectives of VOD and AVC systems are the same: to minimize energy consumption of ventilation, subject to conditions (1) or (3) of the required amounts of air in working areas, in order to dilute harmful impurities.

For the implementation of VOD-based ventilation systems, as well as of AVC systems, it is necessary to find the following parameters:

1. Passive regulation: placement and regulation of stoppings and ventilation doors.
2. Active regulation: placement of fans; variable impeller rotation frequencies and vane angles.

If we compare the classification of ventilation control systems given in Tab. 1, and the classification of VOD strategies, it can be concluded that VOD corresponds to ventilation control systems with sets of methods II-2-B and higher. It should be noted that the fourth VOD strategy (positioning) in Russian literature, as a rule, is considered separately – in relation to security issues and warnings of various emergency situations (Babenko & Lapin, 2010). In this sense, it can be accepted that the fourth strategy in Russian literature is combined with the third.

It was previously stated that controlled air recirculation is one of the AVC strategies, but the same is not said of VOD in the literature. As such, controlled air recirculation cannot be considered as an advantage of the AVC system, since this is a matter of a specific regulatory framework in the country. Moreover, controlled air recirculation is not prohibited by regulations. Canada and the US may serve as examples (Hall et al., 1990; Pritchard et al. 2013). The article (Hall et al., 1990) describes a study on controlled recirculation in potash mines in Canada to determine its feasibility for reducing winter heating costs by reducing the intake airflows. The article (Pritchard et al. 2013) shows an example of controlled district recirculation systems at a nonmetal trona mine in Wyoming. Thus, controlled recirculation is still likely to act as a VOD strategy.

Thus, we can conclude that the VOD and AVC approaches are very similar. The only notable difference between VOD-based ventilation and the AVC system is the use of an optimal control algorithm for fan and ventilation door controllers.

5. Algorithm for optimal mine ventilation control

In this section of the paper, we will focus on the optimal control algorithm, which is the basis of the software aspect of the AVC system. For a better understanding of the role of the algorithm in the overall AVC system, a simplified block diagram of the AVC is presented below (see Fig. 1). In fact, it will be more complicated and will contain many blocks for working out potential emergency modes of operation. In this paper, we will focus on the normal operation of the ventilation control system. In the block diagram, the orange block calculates the control pulses for the frequency converter of the fan and for the electric drives of the ventilation doors. It is this block that uses the optimal control algorithm, which will be discussed later.

Formulation of an algorithm to provide the most energy-efficient ventilation mode requires the introduction of a new concept: automated ventilation door (AVD) connection. AVD connection is an assembly of several ventilation doors located near the common junction of mine airways that perform a common function of distributing airflow across this junction (see Fig. 2). AVD connection is a series-type connection of two groups of ventilation doors: the inlet and outlet groups, each of which consists of a parallel connection of ventilation doors. The inlet group controls airflow distribution in the parallel branches before the junction, while the outlet group controls airflow distribution in the parallel branches after the junction. The parallel branches can represent the return airways of either the main directions or of the panels. This is determined by the scale of the AVC system used – whether it involves the ventilation system of the entire mine, or individual main directions or panels.

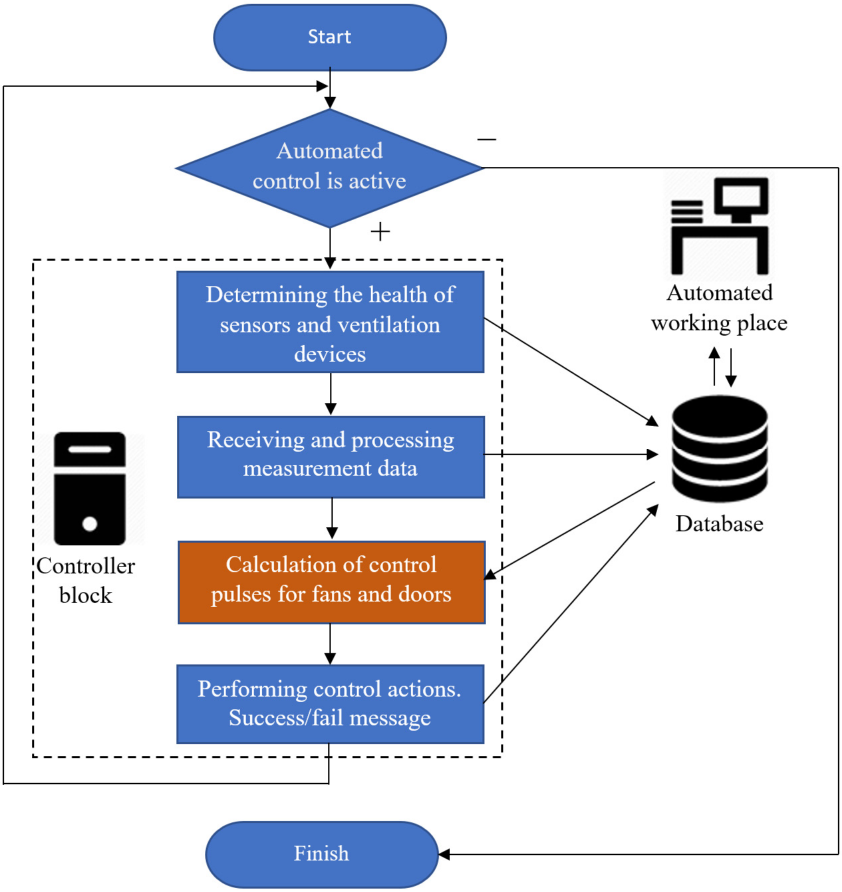

Fig. 1. Block diagram of the AVC system

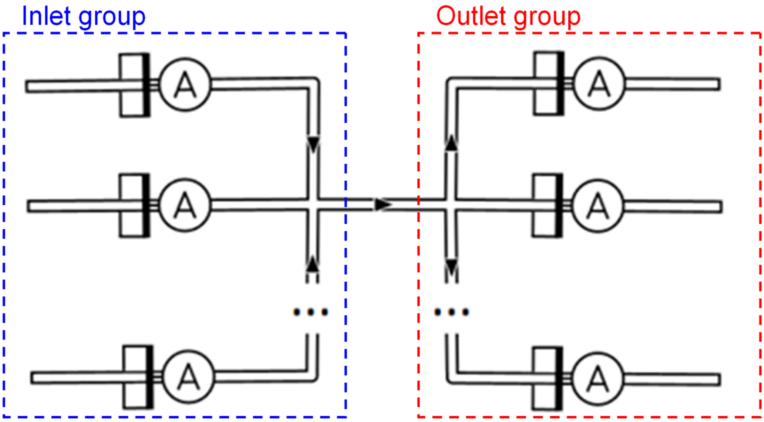

Fig. 2. AVD-connection

First, let us consider the situation of a unique main fan and an arbitrary number of AVD connections. Each ventilation door and the main fan involved in AVC are equipped with an air velocity sensor that is able to measure the air velocity in real time. The stationary sensors mounted on the roof of the airways are usually used for measuring air velocity. Fig. 3 shows an example of such a sensor: an SRSV 01 sensor developed by Ingortech company. It has a measuring range for air velocity from 0.1 to 30 m/s. The permissible basic absolute error of the sensor in the range from 0.6 to 30 m/s is 0.09 + 0.02*V (where V is the measured value of velocity). The velocity sensor is usually located in a straight part of the mine airway at a certain distance (10-20 m) in front of the ventilation door. Before use, the sensor should first be calibrated by comparing its readings with the measured average air velocity in the mine airway.

Fig. 3. SRSV 01 stationary sensor of air velocity

Information about the actual air velocity is transferred to the main controller block, which calculates driving pulses for the ventilation doors, the main fan impeller, and vane angles (see Fig. 4). The driving pulses depend on actual airflows in the mine; the airflow's lower limits are calculated using the technique of calculation of the required amount of air, taking into account the mathematical form of the expressions:

$$\Delta n = G\Delta t \tag{4}$$

$$\Delta\varphi_i = F_i\Delta t \tag{5}$$

Here, Δt is the time step of controller actions, G is the control impulse of impeller rotation frequency; F_i is the control impulse of the i-th ventilation door; Δn is the increment of the main fan rotation frequency, and $\Delta\varphi_i$ is the increment of the turning angle of the i-th ventilation door.

The parameter φ_i is the measure of the ventilation door opening. It may be the turning angle of the louvers or the lifting height of the leaf (see Fig. 5). The calculation of time steps Δt in expressions (4)-(5) is based on the features of the technical implementation of control devices (frequency converters for fans, electric drives of ventilation doors). It is not entirely correct to call this parameter a "time step" from a technical point of view. However, from the point of view of the mathematical representation of the control system, we consider this appropriate.

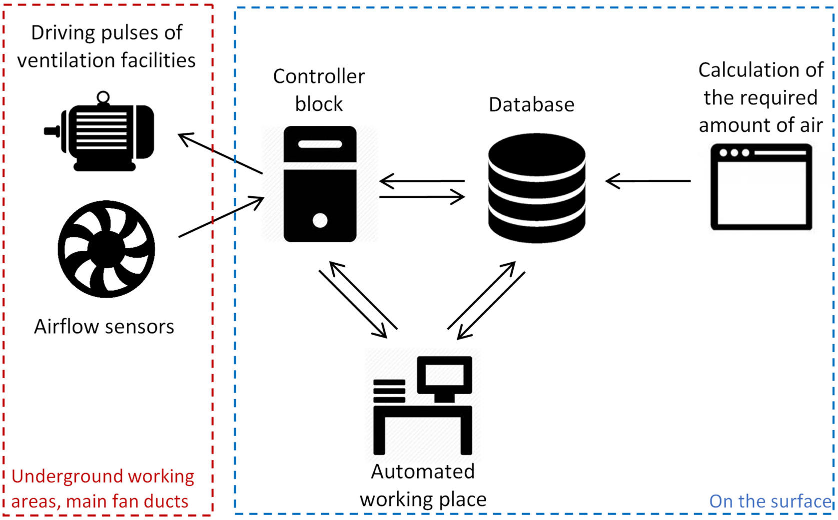

Fig. 4. Process scheme of the AVC system

Fig. 5. Automated ventilation doors: vertical lift of the leaf (left), turning louvers (right)

The mathematical form of expressions (4)-(5) used for calculating driving pulses can be determined from a basis set of logical rules for energy-efficient ventilation control. This set contains rules covering all possible deviations of the current mine ventilation mode from the energy-efficient mode. The basis set of rules developed the for main fan and ventilation doors consists of the logical control rules given below.

Logical control rules for ventilation doors:

1.1. Each ventilation door must open if air deficiency is detected at this door or at any ventilation door in sequence.
1.2. Each ventilation door must close if air deficiency is detected at any ventilation door in parallel.
1.3. Each ventilation door must close if air excess is detected at this door and in all ventilation doors in sequence.

Logical control rules for the main fan:

2.1. Impeller rotation frequency of the main fan must increase if air deficiency is detected at any ventilation door in the mine.
2.2. Impeller rotation frequency must decrease if air excess is detected at all ventilation doors.
2.3. Impeller rotation frequency must decrease until one ventilation door is completely open.

Rule 2.3 for the man fan stems from the fact that one ventilation door in energy-efficient ventilation mode is fully opened. The corresponding mine zone controlled by the open ventilation door is the most hard-to-ventilate zone. Hence, the algorithm seeks a solution "blindly" without any information about the topology of a real mine ventilation network, analysing the energy efficiency of a current ventilation mode by seeking the most hard-to-ventilate zone, using the measured data from ventilation door turning angles and air velocity sensors.

Air deficiency can be calculated by the formula $\Delta Q_i^- = \max\limits_i \left(0, Q_i^{(\min)} - Q_i\right)$, where the index i ranges from 1 to N_{VD} – the number of ventilation doors. Consequently, air excess can be calculated using the formula $\Delta Q_i^+ = \max\left(0, Q_i - Q_i^{(\min)}\right)$. Here, $Q_i^{(\min)}$ denotes the lower limit of the airflow in the i-th ventilation door.

The presented set of rules can be written as mathematical expressions.

The formula for the control impulse of the i-th ventilation door:

$$F_i = I_{VD}\left(\Delta Q_i^+ - \sum_j \Delta Q_j^+ + \sum_{k \neq i} \Delta Q_k^- + \Delta Q_i^- \cdot f_{OF}\right) \tag{6}$$

where I_{VD} is the regulation intensity of the ventilation door turning angle, and f_{OF} is the overflow function determined as:

$$f_{OF} = \begin{cases} 1 & \text{if all ventilation doors in sequence have excess of air} \\ 0 & \text{in all other cases} \end{cases}$$

The formula for the control impulse of impeller rotation frequency:

$$G = I_F\left(\max_i\left(\Delta Q_i^+\right) - \min_i\left(\Delta Q_i^-\right)\right) + A_F \min_i\left(\varphi_i\right) \tag{7}$$

Here, I_F is the regulation intensity of impeller rotation frequency, A_F is the intensity of the main fan and doors conjunction, and φ_i is the turning angle of the i-th ventilation door.

The most interesting is the last term in expression (7). It provides a reduction in the frequency of rotation of the main fan impeller until at least one of the ventilation doors is fully open. This ensures the fulfilment of rule 2.3. It is necessary to carefully select the control parameter A_F. It is recommended to avoid both large values of the parameter A_F and values that are too small. At very large values of this parameter, the fan speed is excessively underestimated, while at values that are too small, the term ceases to affect the impeller rotation frequency in principle. The optimal range for this parameter is approximately the following: $A_F = 0.01...0.1 I_F$.

With a head-capacity curve, we get the equation:

$$H = H(Q,\alpha) \cdot n^2 \tag{8}$$

The operating point of the main fan (Q, H) can be achieved by an infinite set of α-n combinations. The regulation of the vane angle α using (8) with fixed Q and H allows for the determination of the maximum achievable efficiency of the fan without changing its operating point. In this case, the vane-angle control for the fan can be carried out in parallel with its frequency regulation (4). The changes in the vane angle $\Delta\alpha$ and the corresponding rotation frequency Δn are coupled as:

$$0 = \frac{\partial H}{\partial \alpha}(Q,\alpha) \cdot n^2 \Delta\alpha + H(Q,\alpha) \cdot 2n\Delta n \tag{9}$$

The situation of several main fans is considered below for mine 4-RU.

If all automated ventilation doors in the mine operate in parallel, expression (6) can be simplified. Thus, we have:

$$F_i = I_{VD} \Delta Q_i \tag{10}$$

For simplicity's sake, formulas (4)-(5) are written using the proportional term only. A more complicated control algorithm applicable in practice should also contain an integral, as well as the derivatives of G and F_i. Regulation intensities for all control terms can be determined in the process of AVC system start-up and adjustment in the mine.

6. Use of controlled recirculation

The scheme of controlled recirculation for the U-tube ventilation system is presented in Fig. 6. The ventilation network segment to the right of the recirculation cross-cut represents the recirculating contour.

The main idea of controlled recirculation is to provide the required recirculation fraction $F_i^{(\max)}$ in each recirculation contour № i.

$$F = \frac{Q_r}{Q_{fr} + Q_r} \tag{11}$$

$$\Delta n_i = \Delta t \cdot C_i \left[F_i^{(des)} - F_i \right] \tag{12}$$

where C_i is the regulation intensity of rotation frequency n_i of the recirculation fan, Q_r is the recirculated airflow, and Q_{fr} is the intake (fresh) airflow. The recirculation fraction $F_i^{(des)}$ can be chosen individually for each mine in accordance with its gas-bearing capacity, the number of operation equipment items, the number of people, air leakages, recirculation fan performance, etc.

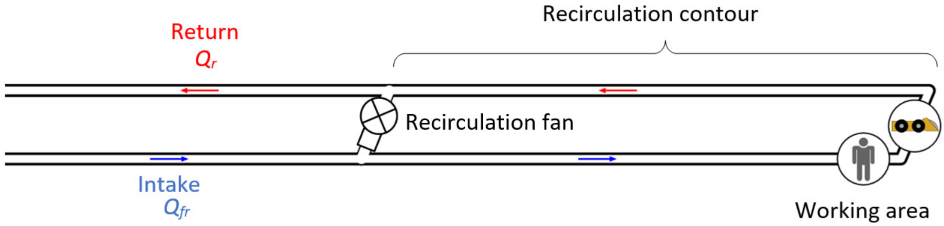

Fig. 6. Scheme of controlled recirculation

In some cases, the controlled recirculation mode is defined by setting the amount of recirculated airflow. For example, for 3-RU and 4-RU mines, the design value of the amount of recirculated air is usually 1500 m^3/min. This value is determined empirically. The calculation of the recirculation coefficient in this case is based on the amount of recirculated air and the required amount of air in the direction. The value of $F_i^{(des)}$ usually varies in a range from 0.3 to 0.7. Another option is direct calculation of the recirculation coefficient $F_i^{(des)}$. by the formula:

$$F = \min\left(k\frac{C_{\max}}{C_{meas}}, F_{\max}\right) \tag{13}$$

where C_{meas} is the gas concentration measured on the return airways before the junction of re-used and fresh airflows, $C_{\max}$ is the maximum permissible concentration of considered gas (CO, NO2, CH4, H2), and $F_{\max} < 1$ is the maximum permissible upper value of the recirculation fraction determined at the mine; k is a coefficient equal to 0.3 for toxic gases and 0.1 for combustible gases (obtained on the basis of paragraph 208 of the Belarusian Regulations for Occupational Safety).

The system of equations (4)-(12) serves as a basis for applying the algorithm for optimal mine ventilation control in the case of a unique main fan. This algorithm and the developed AVC system have been previously tested on the aerodynamic test bench designed and built by engineers and researchers of the Perm Mining Institute. Application of the algorithm facilitated implementation of the AVC system at mines 3-RU and 4-RU of the Belaruskali company. The following section presents two examples of the implementation of the AVC system in Belaruskali's potash mines. Some technical features of implementation are presented.

7. Implementation of AVCS at mine 3-RU

An exhaust U-tube ventilation system has been installed in mine 3-RU with two levels: '–420 m' and '–620 m'. The fresh air enters the –420 m level through intake shaft No. 1 and the –620 m level through intake shaft No. 2. Shaft No. 4 is neutral. The fresh air stream entering each level is divided into three main directions (south, north and east). The return air passes back to the surface via main return airways, shaft No. 3, and the main fan duct, where the VRTsD-4.5 centrifugal main fan is mounted. The main fan is equipped with an impeller frequency controller.

Controlled recirculation, southward in the –420 m level and northward in the –620 m level, reduces the main fan's energy consumption and improves ventilation in distant working areas. The axial fans VME-12a with impeller frequency controllers are placed in recirculation cross-cuts. The diameter of the impeller is 1200 mm, the air flow rate is 1500 m^3/min and the total pressure is 2600 Pa. The required air distribution within the –420 m level is achieved using the automated ventilation doors mounted in the return airways of all six main directions (see Fig. 7).

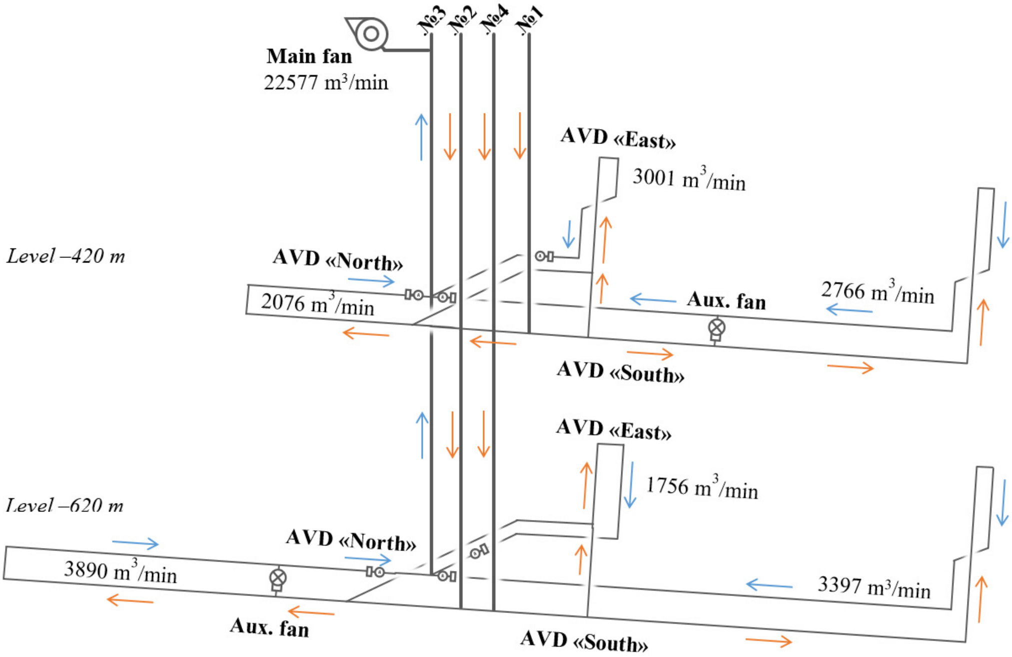

Fig. 7. Simplified ventilation network of 3-RU mine

The gauge stations for air velocity measurements are located in the main return airways near the most distant working areas. The SRSV 01 sensors from Ingortech are used to measure the air velocity in the airways. The parameters of these sensors were given above. The measured values are transmitted from the gauge stations to the AVC central controller and the automation-equipped working place, where they appear on the display. In addition, information about the real-time positions of door turning angles, the impeller rotation frequencies, and the operating conditions of control system devices are displayed.

The air quantity measurements from the main return airways may be entered manually by an operator or read from the database. The database stores information about the required air quantity determined for different ventilation modes. The required amounts of air are calculated with the use of computer software for the Starobin potash deposit. The calculation of the required amount of air is made for each working area individually based on a number of factors: explosive gases, the minimum permissible air velocity, air temperature, dust, the largest number of people per shift. Calculation of the required amount of air for larger sections of mines (blocks, panels, main directions) is carried out by summing the required amounts of air of all working areas in these sections, as well as the air leakages.

The dynamic operation of the AVC system in mine 3-RU allows switching between three possible ventilation modes:

1. mode of mining operations when conveyer belts are active in main directions;
2. mode of repair work when conveyer belts are in the off position in main directions;
3. emergency (stoppage) mode when mining and repair works are off in the main direction and all miners are out of the airways of this main direction.

The use of the AVC system, including controlled recirculation and dynamic operation mode at mine 3-RU, yields a reduction in time-average energy consumption from 2200 kW to 1400 kW.

8. Implementation of AVCS at mine 4-RU

Mine 4-RU also has an exhaust U-tube ventilation system and two levels: –440 m and –670 m. Two main fans are installed at the surface, and the main fan is installed in the –670 m level below the surface. The surface VRTsD-4.5 centrifugal main fans ventilate the –440 m level and the north part of the –670 m level. The main underground fan is a dual Howden 280LY+4HME fan placed in parallel. Since the parameters of both Howden fans are controlled synchronously, we assume that it acts as a single fan unit. It ventilates the southeast part of the –670 m level. All main fans are equipped with impeller frequency controllers.

Intake shafts No. 1 and No. 2 deliver fresh air to the –440 m level. The return air from the –440 m level is exhausted through skip shaft No. 3. The fresh air enters the –670 m level through intake shafts No. 1, No. 2, and No. 5. The return air from the –670 m level comes out to the surface through skip shafts No. 4 and No. 6 (see Fig. 8).

According to the pressure and air quantity survey of the mine ventilation system, changes in the air distribution in one level have no effect on the air distribution in another level. Therefore, separate AVC systems were implemented in each level. The AVC system for the –440 m level is not of interest since it is similar to the AVC system of mine 3-RU. The AVC system used at the –670 m level, in turn, has a distinctive feature: two main fans operating in parallel.

The previously described algorithm (4)-(12) allows for the optimization of ventilation systems with one main fan. Therefore, the following improvement of algorithm (4)-(12) is proposed to organize energy-efficient ventilation at the –670 m level of mine 4-RU.

The idea was to take expression (7) as a basis and apply it to both fans with some weight factors. For this, an influence matrix was introduced:

$$I = \begin{pmatrix} I^{fan1}_{west\ A} & I^{fan2}_{west\ A} \\ I^{fan1}_{east\ A} & I^{fan2}_{east\ A} \\ I^{fan1}_{east\ B} & I^{fan2}_{east\ B} \\ I^{fan1}_{B2} & I^{fan2}_{B2} \end{pmatrix} = \left\{ I^i_j \right\}, \quad I^i_j = \frac{\partial Q_j}{\partial Q_i} \tag{14}$$

In should be noted that we are not the first to use influence matrices. The concept of influence matrices was previously used in other works, both on mine ventilation control (Tsoy, 1975) and on the analysis of airflow stability in ventilation networks (Dziurzyński et al., 2017). In these

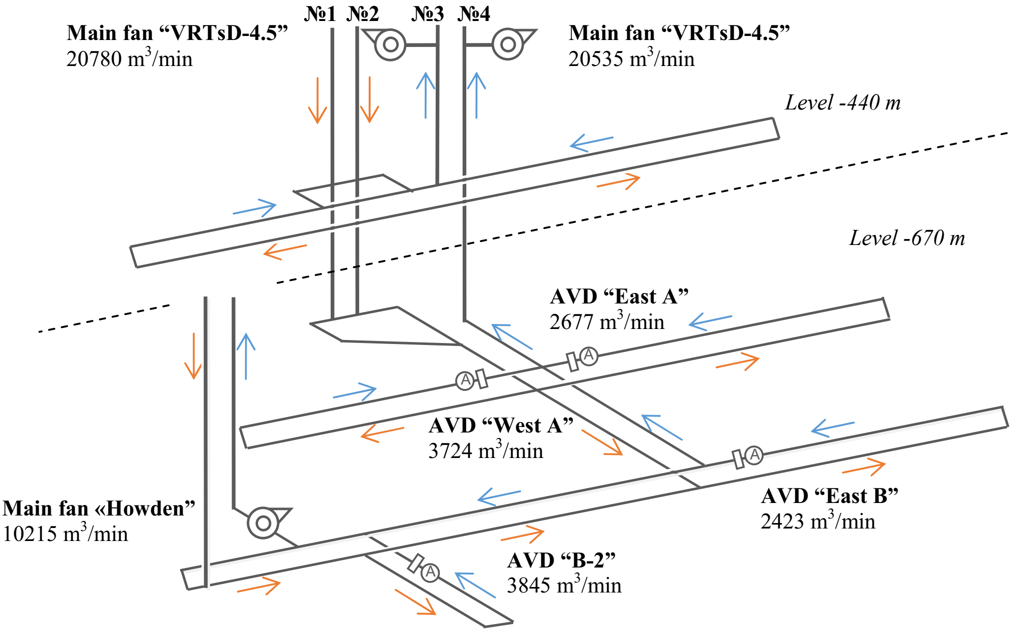

Fig. 8. Simplified ventilation network of 4-RU mine

works, the functional form of the matrix elements is slightly different, but the meaning remains approximately the same.

Two columns represent two main fans ventilating the –670 m level, and four columns are the four main directions of the level with automated ventilation doors. The element I_j^i of the matrix measures the sensitivity to airflow change in the i-th main direction, which is determined by the I airflow through the j-th main fan. In this regard, the matrix of influence includes the information about the topology of the mine ventilation network. Therefore, controlling ventilation with many fans is different from doing so with one main fan, wherein the topology of the mine ventilation network is not used.

However, a simplifying option is possible here, when the influence matrix is set manually and consists of zeros and ones. Value '0' corresponds to the situation when the fan does not affect the ventilation door – and value '1' to when it does. Each ventilation door may be in the zone of influence of only one fan. Thus, it is possible to artificially split the –670 m level control system into two independent parts, each of which can be controlled by algorithm (4)-(12).

This simplification is correct only when, for each ventilation door, there exists a fan whose influence is dominant. The 4-RU mine ventilation system has ventilation doors with a comparable effect of both main fans (AVD 'East B'). Therefore, the control system cannot be split. The determination of the elements of the influence matrix for the 4-RU mine was carried out both experimentally (by measuring air velocities at various operating modes of the fans) and theoretically using the model of the ventilation network. Setting the elements of the influence matrix can also be done expertly; however, in this case, human error will appear, and the resulting ventilation mode of the mine will not be the most effective possible.

Formula (7) for the control impulse of impeller rotation frequency is modified as follows:

$$G_j = I_{Fj}\left(\max_i\left(I_j^i \Delta Q_i^+\right) - \min_i\left(I_j^i \Delta Q_i^-\right)\right) + A_F \min_i\left(\varphi_i\right) \tag{15}$$

The dynamic operation of the AVC system at mine 4-RU is similar to that at mine 3-RU, and exhibits three possible modes of ventilation: mining operations mode, repair work mode, and emergency mode.

The control intensities I_{Fj} and A_F are determined individually for each of the fans. In the case of more than one main fan, the number of fully open ventilation doors in the optimal ventilation mode may be greater than one. If all N main fans have sufficiently different zones of aerodynamic influence in the mine, N ventilation doors will be opened in the optimal ventilation mode.

The use of the AVC system at mine 4-RU, including controlled recirculation and dynamic operation mode, yields reduced time-average energy consumption from 2400 kW to 1200 kW.

9. Conclusions

The paper provides a comparative analysis of two main approaches to mine ventilation control: ventilation on demand (VOD) and automatic ventilation control (AVC) systems. It is shown that both approaches have much in common. The only significant difference between them is the optimal control algorithm used in automatic ventilation control systems. The main idea of the algorithm consists of formulating a basis set of logical rules for achieving energy efficiency (ventilation control). The basis set should contain rules covering all possible deviations of the current mine ventilation mode away from the energy-efficient mode. The mathematical form of the proposed logical rules represents the system of control equations, which can be used for industrial control programming. The main advantage of the algorithm is that it does not require information about the real topology of the mine, nor does it require simulation of air distribution in the mine ventilation network. It can be easily programmed into the microcontrollers of fan frequency converters and the electric drives of ventilation doors. The proposed algorithm is extended to the case of many main fans by introducing an influence matrix. However, in the case that the mine ventilation system has more than one main fan, and their effect on some ventilation doors is comparable, some information on the ventilation network topology is in fact required to determine the elements of the influence matrix. The paper describes the implementation of the proposed system at Belarusian potash mines 3-RU and 4-RU. For both potash mines considered, a significant reduction in the energy consumption for main fans' operation obtained.

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