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Methodological framework for designing ventilation control systems for complex mine ventilation networks

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Abstract
As ventilation networks in modern mines expand, airflow distribution control becomes increasingly complicated due to three factors: insufficient control depth combined with unsynchronized operating schedules of individual mine sectors; increasingly complex aerodynamic interactions between working areas and control devices; and growing system inertia. This highlights the need for a unified approach to designing ventilation control systems for complex networks, so that the conditions under which their implementation is technically feasible and economically justified can be assessed in advance. To achieve this objective, two key tasks were addressed: identifying the appropriate spatial depth and temporal scale of ventilation control. The methodology was based on a mathematical framework for analyzing aerodynamic interactions in branched networks with numerous fans, shafts, levels, and diagonal connections. The framework includes the use of aerodynamic influence matrices, their graphical analysis, clustering, and decomposition of the network into subsystems. Dimensional analysis was also applied to estimate the characteristic times of various dynamic processes in mines. As a result, principles for designing control systems were proposed, including the selection of the control level with regard to the number of air consumers and their operating schedules, as well as matching the control time scale to the characteristic times of ventilation and mining processes. It was shown that the duration of production cycles permits ventilation control to be applied at that level, opening a promising direction for further research. It was also established that, in complex ventilation networks, control algorithms should be designed primarily to maintain the required airflow rate, whereas control based on gas concentration is less effective.

Keywords
mine ventilation, ventilation on demand, mine ventilation networks, ventilation control, aerodynamic influence, spatial depth of control, temporal scale of control

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ

Научная статья

Методологические аспекты создания систем управления проветриванием сложных вентиляционных сетей современных рудников

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Аннотация
По мере развития вентиляционных сетей современных рудников управление воздухораспределением осложняется воздействием трёх факторов: недостаточной глубиной регулирования и несинхронностью графиков работы отдельных участков; усложнением аэродинамических связей между рабочими зонами и регуляторами; ростом инерционности системы. Это обусловливает необходимость разработки единого подхода к созданию систем управления вентиляцией в сложных сетях, позволяюще-

го заранее оценить условия, при которых внедрение таких систем будет экономически оправданным и технически реализуемым. Достижение указанной цели предполагало решение двух ключевых задач: определение пространственной глубины управления и временного масштаба управления. Основой методологии послужил разработанный математический аппарат для анализа аэродинамических связей в разветвлённых сетях с большим числом вентиляторов, стволов, горизонтов и диагональных соединений. Он включает использование матриц аэродинамического влияния, их графический анализ, кластеризацию и декомпозицию сети на подсистемы. С помощью метода размерностей получены оценки характерных времен различных динамических процессов в рудниках. В результате предложены принципы проектирования систем управления, предусматривающие выбор уровня регулирования с учётом числа потребителей и их производственных графиков, а также согласование временного масштаба регулирования с характерными временами аэрологических и горнотехнологических процессов. Показано, что длительность технологических циклов допускает применение регулирования вентиляции на их уровне, что открывает перспективное направление для дальнейших исследований. Установлено, что для сложных вентиляционных сетей алгоритмы управления должны быть в первую очередь ориентированы на поддержание требуемого расхода воздуха, тогда как регулирование по концентрации газов менее эффективно.

Ключевые слова
рудничная вентиляция, вентиляция по требованию, вентиляционные сети, управление проветриванием, аэродинамическое влияние, пространственная глубина управления, временной масштаб управления

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Introduction

As large mineral deposits are developed, mine ventilation networks tend to become highly branched over time. They may include several hundred or even thousands of mine workings, numerous working areas, underground levels, and pressure sources. As the network expands, the nonproductive use of fresh air, that is, so-called air leakage, also increases. Delivering the required volume of fresh air to each working area becomes progressively more difficult, while ensuring this in an energy-efficient manner becomes even more challenging. As a result, mine ventilation costs steadily increase with mining depth, the expansion of the workings network, and rising production rates. Under such conditions, the share of power consumption attributable to ventilation may reach 50% of the total energy used in mining operations [1–3]. Ventilation thus becomes such a costly production process that its optimization can no longer be neglected if a mining enterprise intends to remain profitable.

The number of shafts in mines is usually minimized for economic reasons. However, their air-carrying capacity is limited by the permissible air velocity, which, according to safety regulations, must not exceed 15 m/s. This naturally reduces the maximum allowable airflow through shafts and, in turn, requires more rational and efficient air distribution throughout underground workings.

Energy-efficient ventilation of underground mines requires the use of airflow control systems. The most widespread of these is ventilation on demand (VoD), which provides dynamic adjustment of air supply depending on the current operating conditions [4, 5]. For each shift, a required airflow rate is specified, and the system achieves it by varying the rotational speed of the main fans, adjusting the door opening, and using other control means. This approach has proven effective in relatively small mines with one or several working areas. In such cases, it is generally possible to rely on fairly simple control algorithms for fan installations and ventilation doors.

However, in branched ventilation networks serving numerous air consumers, the effective use of ventilation control systems remains an open issue. There are known cases where simple control schemes that distribute airflow only among the main mine districts fail to deliver appreciable energy savings [6]. This is primarily due to insufficient control depth and the limited overlap between the operating schedules of development and production districts. In this context, control depth refers to the hierarchical level at which ventilation regulators are installed, that is, the extent to which ventilation doors are positioned beyond the shaft station and the main drifts to redistribute airflow among individual sectors of the network. For example, in the Verkhnekamsk potash mines, if ventilation doors are installed only on the main ventilation drifts near the shaft station and regulate only the overall airflow by direction, the system cannot accurately redistribute airflow among panels and blocks within the same direction. Consequently, a significant portion of the potential benefit is lost.

The growing complexity of airflow distribution control in developing ventilation networks cannot be explained by this factor alone. Two additional aspects are also of major importance.

First, aerodynamic interactions between working areas and control devices become increasingly complex. In practice, a ventilation network cannot always be represented as a simple system of several parallel airways, each controlled by a separate fan or door. Working areas are often connected in series or by diagonal links, so that a single control device may affect several air consumers to different extents [7].

Second, ventilation system inertia increases. The greater the total length of the main ventilation airways and the more complex the network, the longer it takes for a new airflow distribution to become established after the control settings have been changed. This limits the performance of the control system, which must operate on a time scale consistent with the transition of the network to a new steady state. In large networks, the control system is physically unable to respond to short-term fluctuations in airflow rate or gas concentration; such variations must therefore remain outside the control range.

This raises an important question: can a unified approach be developed for designing ventilation control systems in complex networks that would make it possible to assess in advance the conditions under which their implementation would be technically feasible and economically justified? Addressing this question requires a conceptual reappraisal of ventilation control, especially in mines with complex ventilation networks. In the present study, complexity is understood specifically in terms of controllability, that is, the presence of one or more of the following factors:

– a large number of ventilation control devices, including fans and ventilation doors;

– numerous working areas connected in parallel, in series, or through diagonal connections, with unsynchronized operating schedules;

– long airways, which increase system inertia.

The **aim** of this study is to develop and substantiate methodological principles for designing ventilation control systems for complex mine ventilation networks while accounting for these factors.

To achieve this aim, two **key objectives** must be addressed:

1. To identify the appropriate spatial depth of control, that is, to determine the hierarchical level at which ventilation regulators should be installed to effectively influence airflow in working areas.

2. To determine the appropriate temporal scale of control, that is, to identify the characteristic times of transient processes that may serve as targets for automatic regulation.

The first objective concerns the placement of negative regulators at underground levels. The key question is where they should be installed in order to exert a significant influence on airflow in the working area and, ultimately, to enable the system to achieve appreciable power savings.

Whereas the first objective relates to the spatial structure of the network, the second concerns its dynamics. More specifically, it requires estimating the characteristic times of unsteady aerological processes and comparing them with the response time of the control system.

Some dynamic processes are so rapid that they cannot be regulated by means of ventilation doors or fans, as any such attempt would destabilize the system. These include gas emission from the rock mass [8], the aerodynamic effects produced by moving mining equipment [9], and similar phenomena. Other processes are much slower, for example thawing of the rock mass [10], for which periodic manual adjustment of ventilation windows, once a week or once a month, is sufficient. It is therefore essential to identify processes whose duration is comparable to, but not shorter than, the response time of the control system and to use them as the basis for automatic regulation.

The development of a unified approach to mine ventilation control systems has been discussed in earlier studies. Significant contributions were made in [11–13], which established the theoretical foundations for automated airflow distribution control. In particular, [11] introduced the term *automated ventilation control system*. The authors of [12] were the first to emphasize the need to account for the different inertia of aerodynamic and gas-dynamic processes arising from different rates of disturbance propagation, and they also proposed a classification of ventilation networks into easy-to-control and difficult-to-control systems. In [13], an optimality criterion for ventilation network control was formulated, and methods for solving the corresponding optimal control problem were proposed.

The present study builds on the definition of complex ventilation systems proposed by S.V. Maltsev[1], while substantially extending it in the context of control tasks.

It should also be noted that the above studies considered optimal airflow distribution control pri-

[1] Maltsev S.V. Research and development of methods for determining the aerodynamic parameters of complex ventilation systems in underground mines. [Diss. ... Cand. Sci. (Eng.)] Perm; 2020. 148 p. (In Russ.)

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marily through computer models of ventilation networks. The present study, by contrast, focuses on the application of automatic control theory. Thus, despite the extensive theoretical foundation already available, the methodology for designing ventilation control systems for mines with complex ventilation networks has not yet been addressed as a distinct subject in its own right.

Determining the spatial depth of ventilation control

Ventilation networks in modern mines are highly branched structures in which the airflow is split not once or twice, but many times. This is especially evident in potash mines (Fig. 1), where a *central ventilation system* is typically used.

Air entering through the intake shaft is first distributed among the main mine districts, then routed into the intake panel drifts, including the haulage and conveyor drifts, and subsequently into the block workings. If ventilation doors are installed only on the return drifts of the main directions, it becomes impossible to regulate airflow distribution among the individual branches within those directions, that is, at the panel and block levels.

This is due to the mining method used. At the Verkhnekamsk deposit, room-and-pillar mining with mechanized extraction by continuous miners is employed. Under these conditions, many production faces, often several dozen, operate simultaneously in different panels and on asynchronous schedules. On average, downtime at each face may reach 10 h per day. However, because a single ventilation door supplies air to several faces at once, it is practically impossible to reduce the total airflow rate in the mine [6].

By contrast, installing doors at every panel within a given direction would substantially increase their number and, consequently, the cost of implementing the ventilation control system. In addition, doors would have to be installed on all parallel branches, that is, all panels within that direction, in order to eliminate parallel aerodynamic connections. Otherwise, air would short-circuit through the branch not equipped with a flow-restricting device, effectively reducing the potential energy-saving effect to zero.

Thus, the placement of ventilation doors should be determined with reference to two key factors:

– the number of air consumers served by a single automatic ventilation door;

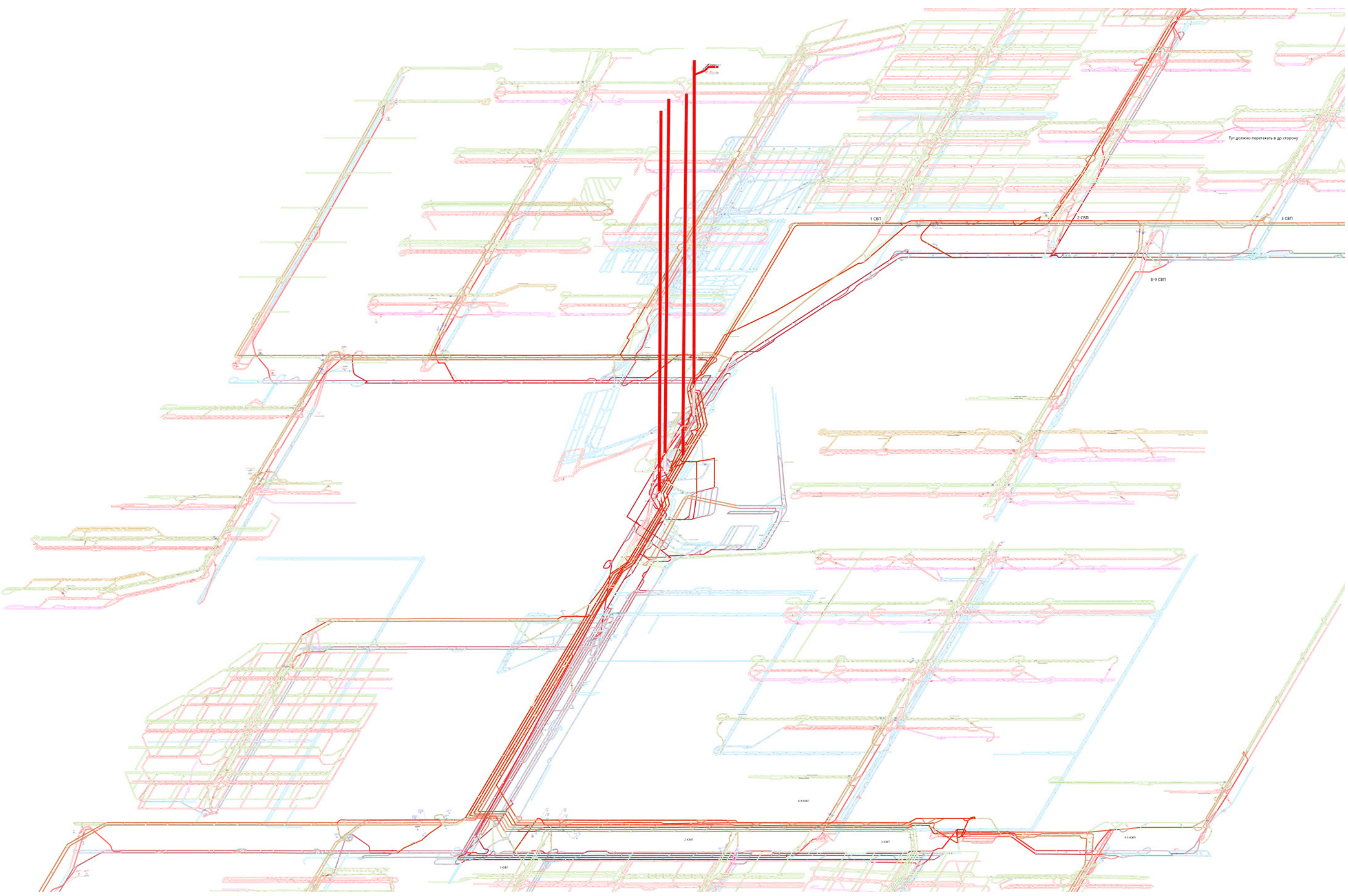

Fig. 1. Fragment of the ventilation network of a potash mine in the Verkhnekamsk deposit (generated using the Aeroset software package)

– the degree of overlap between the operating schedules of these air consumers.

If the number of consumers is large and their schedules are substantially out of phase, appreciable power savings are unlikely to be achieved. In such cases, the doors should be installed one hierarchical level lower, after the next airflow split into individual sectors, and the number of air consumers served by each automatic door should then be reassessed.

Ideally, one ventilation door should serve one consumer. In practice, however, this is not always feasible because of the large number of working areas, their high mobility, the rapid advance of the mining front, continual changes in active locations, and the influence of additional disturbing factors near individual working areas, such as auxiliary fans or moving mining equipment. Accordingly, identifying a compromise solution usually requires comparing the capital cost of installing ventilation doors with the savings in operating costs achieved through lower fan power demand.

This situation is not typical of the potash mines of the Starobin deposit, where longwall mining with caving is predominantly used. In the main directions of the ventilation networks at these mines, there are relatively few high-capacity working areas, namely longwalls, which makes it possible to achieve substantial power savings [5].

A different situation arises when ventilation control systems are designed for mines with a *flank ventilation system*. Examples include the copper-nickel mines in northern Krasnoyarsk Krai, which typically have 5–7 shafts, 2–4 main fan installations, and numerous underground levels. Fig. 2 shows the ventilation network of one such mine, including three main fans, seven shafts, and more than ten underground levels.

Whereas in mines with a central ventilation system the topological relationship between individual air consumers and ventilation doors can still be identified with reasonable clarity, in mines with a flank ventilation system it becomes much more difficult to trace airflow paths, determine which workings exert the strongest influence on particular air consumers, and establish where ventilation doors should be installed.

This complexity is primarily due to the large number of ventilation raises, inclines, connecting ramps, and other workings that create numerous diagonal connections and make the overall airflow pattern difficult to interpret. In this context, it is difficult to determine the required control depth and the corresponding arrangement of ventilation doors across underground levels.

To solve this problem, the present study proposes the use of aerodynamic influence matrices. These matrices make it possible to quantify how a change in the *i*-th control parameter affects the airflow rate at the *j*-th consumer.

If a tentative set of ventilation doors has been selected and the suitability of their locations needs to be assessed, an aerodynamic influence matrix may be calculated in the form

$$I_{ij} = \frac{R_{0j}}{Q_{0i}} \frac{\Delta Q_i}{\Delta R_j}, \qquad (1)$$

where R_{0j} is the initial aerodynamic resistance of the *j*-th door, $N \cdot s^2/m^8$; Q_{0i} is the initial airflow rate at the *i*-th consumer, m^3/s; ΔQ_i is the change in the total airflow rate at the *i*-th consumer in response to a change in the resistance of door *j*, m^3/s; ΔR_j is the change in door resistance, $N \cdot s^2/m^8$.

The coefficients of the aerodynamic influence matrix in Eq. (1) make it possible to identify which ventilation doors have a strong effect on the airflow rate at a given air consumer while causing only minimal disturbance elsewhere in the network. This is determined by both the magnitude and the sign of the corresponding matrix elements.

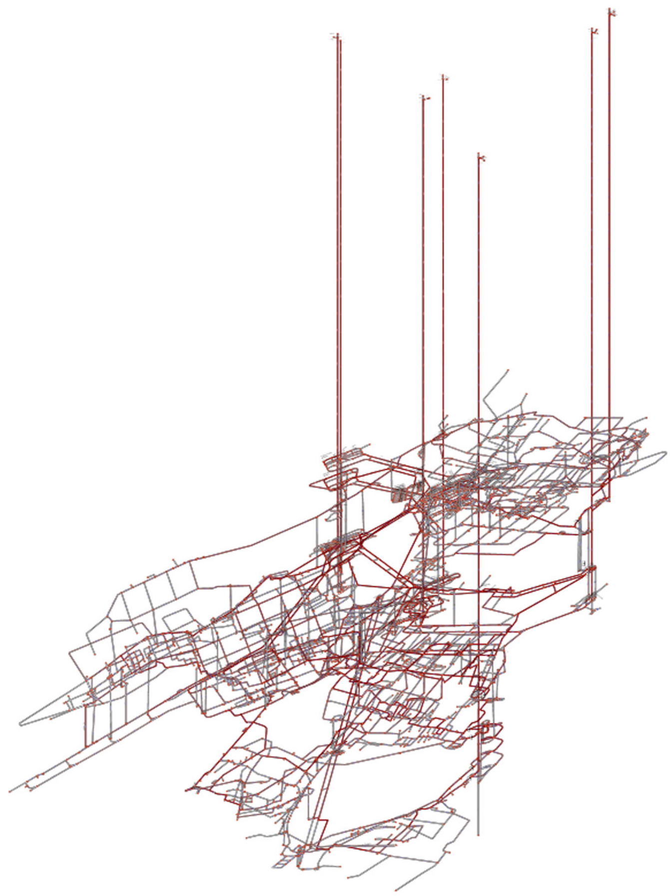

Fig. 2. Ventilation network of a copper-nickel mine in Krasnoyarsk Krai

A similar matrix may be constructed to evaluate the effect of the main fan installations on the airflow rates at the air consumers:

$$I_{ij} = \frac{n_{0j}}{Q_{0i}} \frac{\Delta Q_i}{\Delta n_j}, \qquad (2)$$

where n_{0j} is the initial impeller rotational speed of the j-th fan installation, rpm, and Δn_j is the change in the impeller rotational speed of the j-th fan installation, rpm.

Mathematically, Eqs. (1) and (2) represent the Jacobian of the ventilation network. They are closely related to the sensitivity matrices used in stability analysis of mine ventilation networks [14, 15], but in this case they are expressed in normalized dimensionless form, which allows direct comparison of matrix elements for workings with substantially different airflow rates.

These matrix coefficients are not fixed; rather, they depend on the initial airflow rates Q_{0i}, aerodynamic resistances R_{0j}, and fan rotational speeds n_{0i}. Consequently, if the mine ventilation regime for which matrices (1) and (2) were derived changes substantially, their numerical values may also change appreciably. In addition, qualitative changes may occur, especially in parts of the network containing diagonal connections, reflecting the variable nature of aerodynamic interactions and highlighting potentially vulnerable zones susceptible to ventilation instability.

The corresponding matrix was constructed to assess the effectiveness of the selected ventilation-door locations in the copper-nickel mine shown in Fig. 2. For six aggregated air consumers, that is, mining districts comprising several working areas, matrix (1) identified the ventilation doors with the greatest influence on their ventilation (Fig. 3).

The blue and light-blue cells correspond to cases where $I_{ij} < 0$, that is, where an increase in ventilation-door resistance leads to a decrease in the airflow rate at the given consumer. At the same time, the matrix also contains elements for which $I_{ij} > 0$. In such cases, increasing door resistance causes the airflow rate to increase at some air consumers located on airways parallel to the corresponding door.

The ventilation door exerting the strongest negative influence was identified for each air consumer. This information was then used to assign control functions among the doors so as to ensure the required airflow rate at each consumer.

An approach of this kind, conceptually close to clustering methods widely used in data analysis, often reveals distinct clusters in the matrices, that is, groups of air consumers and doors that are closely interconnected but only weakly connected to the rest of the mine. In such cases, the control system of a complex mine can be organized as several mutually independent subsystems, which greatly simplifies its practical implementation.

Such clusters can be identified, for example, by introducing a threshold value for $|I_{ij}|$ (Fig. 4). Once all cells with values below this threshold are removed, it becomes clear which ventilation doors should be assigned to control which air consumers. At the same time, the need for some doors may be called into question, as in the case of doors 1, 7, and 9 in the mine considered here.

This matrix-based approach was applied in the development of ventilation control systems for three copper-nickel mines in Krasnoyarsk Krai. Because these mines use full-seam mining combined with drill-and-blast development, work shifts are highly synchronized. This makes it possible to distinguish several relatively large districts containing multiple working areas; in the mine considered above, six such districts were identified (see Figs. 3 and 4). In such cases, dynamic intrashift airflow distribution control can deliver substantial average daily energy savings, which ranged from 10.9 to 20.1% across the three mines studied.

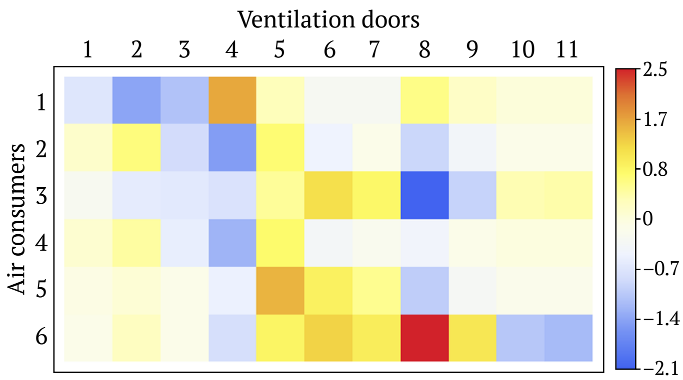

Fig. 3. Aerodynamic influence matrix for air consumers (production districts) in the copper-nickel mine

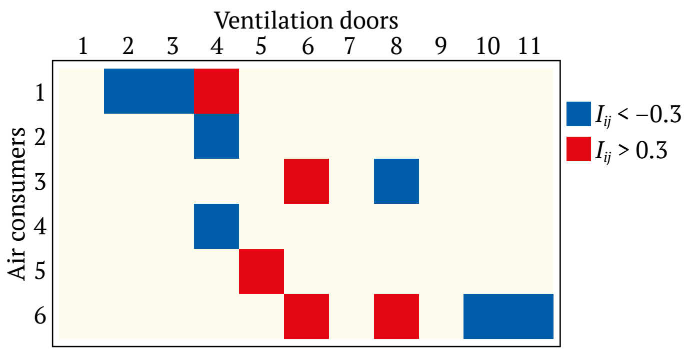

Fig. 4. Binarized aerodynamic influence matrix for air consumers in the copper-nickel mine

Determining the temporal scale of ventilation control

Aerological processes in the mine atmosphere are inherently unsteady and differ substantially in their characteristic time scales.

Fast processes. The fastest processes, such as the passage of a shock wave during drilling-and-blasting operations or methane outbursts, as well as the propagation of an acoustic wave during the rapid opening or closing of stoppings, are characterized by the following time scale:

$$\tau_1 = \frac{L}{c}, \tag{3}$$

where L is the length of the main airway in the ventilation network, m, and c is the speed of sound in air, m/s. For L = 10 km, this gives $\tau \approx$ 30 s.

On such a short time scale, the airflow distribution in the network obviously cannot reach a steady state. Establishing a new distribution requires the repeated passage of acoustic disturbances [16]. The characteristic time required for the ventilation network to reach a steady airflow distribution can be estimated using the equation proposed in [17]:

$$\frac{\rho L}{S}\frac{dQ}{dt} = H - RQ^2, \tag{4}$$

where ρ is the air density, kg/m^3; S is the cross-sectional area of the working, m^2; Q is the airflow rate, m^3/s; H is the pressure drop, Pa; R is the aerodynamic resistance, N·s^2/m^8.

In this case, the characteristic time

$$\tau_2 = \frac{\rho L Q}{SH} \tag{5}$$

is on the order of tens of minutes.

Intermediate time scales. The characteristic times of production cycles depend on the specific type of operation. They may be on the order of:

– minutes, during the movement of load-haul-dump machines or haul trucks used to re-enter dead-end workings after blasting, as well as during the operation of continuous miner systems, for example in the Verkhnekamsk potash mines;

– hours, during post-blast ventilation of blind headings, maintenance operations, and similar activities.

In the general case, the time parameter τ_3, which reflects the cyclicity of production operations in working areas, should be determined individually. The same applies to τ_4, which characterizes shift duration (production, maintenance, or shutdown).

Slow processes. The longest-term variations are associated with thermal processes in the rock mass, including thawing, as well as seasonal changes in natural ventilation pressure, and may persist for weeks or months. Their characteristic time may be estimated from [18] as:

$$\tau_5 = \frac{R^2}{a}, \tag{6}$$

where R is the characteristic transverse dimension of the mine working, typically on the order of several meters, m, and a is the thermal diffusivity of the rock ($\approx 10^{-6}$ m^2/s).

Associated unsteady processes. Other processes also occur in mines, including the release of dust, methane, and hydrogen sulfide from the rock mass, as well as emissions from diesel-powered equipment. Their temporal behavior is sometimes correlated with equipment operation, but in many cases follows a different pattern. For example, gas emission from the rock in potash and coal mines may vary over time as a result of random processes, with characteristic fluctuation times on the order of minutes [8, 11].

This raises an important question: which parameter should be used to control ventilation doors and fans? Some authors [19–21] propose relying on direct gas analyzer readings at the working face. However, in mines with complex ventilation networks, this approach may be impractical because many gas-emission processes vary on time scales much shorter than the response time of the control system. In such cases, a more reliable control criterion is compliance with the required airflow rates determined in accordance with approved procedures. Since these values are relatively stable over time, they can serve as a sound basis for the design of automated ventilation control systems.

Thus, all unsteady processes occurring in mine ventilation networks can be classified according to their characteristic times. This makes it possible to place them on a common time scale together with the characteristic response time of the ventilation control system, τ_y. The response time, however, should not be shorter than τ_2, the time required for a steady airflow distribution to become established after changes have been introduced into the network (Fig. 5).

Within this time scale, it is possible to identify the range of characteristic times over which unsteady processes can and should be regulated by the ventilation control system. Processes whose time scales fall outside this range are either not amenable to effective control or are not worth regulating from an economic or operational standpoint.

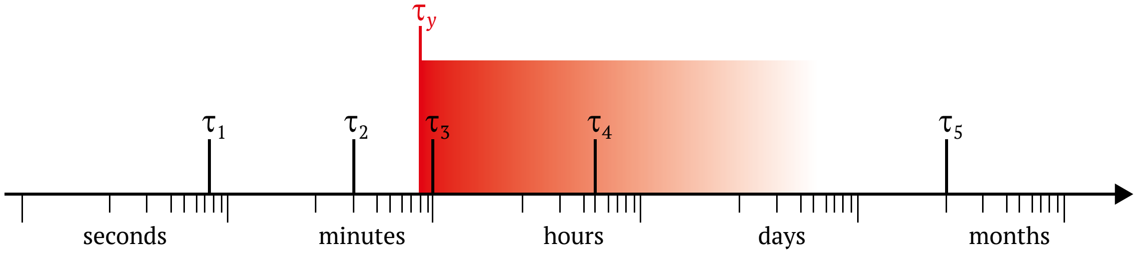

Fig. 5. Characteristic time scales of the main processes and control response time

Fig. 5 shows, in particular, that the primary objects of control are production processes associated with operations in working areas, as well as transitions between different shift states, namely production, maintenance, and shutdown. The latter, referred to as dynamic intershift control [22], most often serves as the basic implementation level of ventilation on demand in mines. It is based on fixed setpoints, that is, airflow rates specified at the dispatcher workstation and usually assumed to remain unchanged within each shift. This approach ensures a high level of reliability and operational stability, as repeatedly confirmed in practice [5, 23, 24].

At the same time, processes characterized by the time scales of production cycles within a shift, such as vehicle entry and exit, truck loading and unloading, and similar operations, may also be sufficiently long to permit regulation in some cases. This opens up a promising avenue for future research, namely the development of intrashift ventilation control methods. Their implementation would increase the flexibility of ventilation-on-demand systems, better align air supply with the actual pattern of production operations, and thereby create additional potential for energy savings.

Conclusion

The main scientific and practical findings of the study can be summarized as follows.

1. Three main factors were identified that increase the complexity of airflow distribution control as the ventilation network develops: insufficient spatial control depth combined with unsynchronized mining schedules in different districts; increasingly complex aerodynamic interactions between individual working areas and airflow control devices; and growing system inertia, which lengthens the response time to disturbances.

2. Methodological principles were proposed for designing ventilation control systems for mines with complex ventilation networks: when selecting the control level, it is necessary to take into account the number of air consumers served by a single automatic door and the extent to which their operating schedules overlap, while the temporal scale of ventilation control should be matched to the characteristic times of ventilation and mining processes.

3. A new mathematical framework was developed for analyzing aerodynamic interactions in networks with large numbers of fans, shafts, levels, and diagonal connections. The framework is based on aerodynamic influence matrices, their graphical analysis, clustering, and the decomposition of the network into mutually independent subsystems.

4. It was shown that the characteristic times of production cycles such as vehicle entry and exit, loading, and unloading may be sufficiently long to permit ventilation control at the level of these processes, thereby opening a promising direction for further research.

5. In complex ventilation networks, control algorithms should primarily be aimed at maintaining the required airflow rate, whereas control based on gas concentration is less suitable because of its rapid variability in response to gas emission from the rock mass.

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