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Effectiveness of ventilation regulation in a simple diagonal system of underground mines

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Abstract

Purpose. Each ventilation system has its own important elements, such as the various branches of the system, which can be connected in a normal and diagonal pattern, ventilation regulators and fans. Based on a professional approach to the analysis of this aeration system, a comparison of reliability results has been conducted, which indicates the real state of the microclimate in underground mines, affecting the increase in the prospects for the development of mining activity.

Methods. This paper deals with the problem of ventilation in underground mines, especially in diagonal systems, and the importance of regulating ventilation to provide the required amount of air (Q, m^3/min) through the entire system, taking into account the determination of the main fan depression.

Findings. To ensure the required (designed) amount of air through the system branches, various methods of effective regulation are used in mining engineering. Therefore, based on research and measurements in different mine workings, our findings provide complete safety and comfort of microclimate during mining activity.

Originality. The measurements performed and the database created according to the values and results obtained from the analytical calculations present the best possible estimate, which is substantiated in the paper.

Practical implications. The problem of calculating and regulating aeration for a simple diagonal system has been solved, taking into account the determination of the main mine fan depression before and after the use of aeration regulators.

Keywords: *volume of air, ventilation system, adjusting sockets, aerodynamic resistance, ventilator, mine*

1. Introduction

The ventilation system in underground mines is often considered by various authors as the blood circulation system in the human body. In this case, the fresh air ways that transport oxygen to the working areas, as well as the impure air ways that ensure its removal from the working fronts and connection with the mine surface, are compared with veins in the human body.

Thus, ventilation systems are important to ensure that clean air circulates in sufficient amount and in a certain direction throughout the entire underground network of mine workings, as well as in each particular mine working of this network [1]. Therefore, for the optimal solution of this system, it is necessary to determine the source point of the depression and the direction of its action, the aerodynamic resistance of the branch between the joints and the total amount of air (Q, m^3/min) that must enter the system or even leave the system [1]-[3].

The air constantly circulating in various underground spaces of the mine is subject to various influences. Thus, for a correct and adequate interpretation, it is necessary to know the basic principles of aerodynamics. In addition, a detailed analysis of the state and control of aeration using the necessary equipment is required in order to objectively assess the microclimatic aeration conditions throughout the mine or in its individual parts [4], [5].

The problem of ventilation systems is to theoretically determine the direction of currents in the branches of the system, the aerodynamic resistance or equivalent pitch of the system as a whole, the amount of air distributed in each branch of the system, and the height of the total depression in the system as a whole, the value of which determines the characteristic of the fan or fans for the underground mine ventilation [5]-[7]. Improvements in microclimatic conditions, achieved through various regulators in underground mine aeration systems, always significantly increase the productivity of mines [7]-[9].

The purpose of using regulators is to reduce the amount of air in certain air duct or part of the mine by a certain amount, as well as to orient it in another way or direction [10]. In cases where the amount of air in a part of the mine needs to be increased to a value that is greater than what can be achieved by the system itself, this can be achieved through active regulation [8], [11]. Active regulation means the use of an amplifying fan, which can increase the amount of air in that part of the mine [11], [12]-[14].

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2. Methods

2.1. Aerodynamic resistance

Mine stability has been greatly reduced and the environmental conditions have also been improved by providing a separate ventilation compartment before operation. So, given the fact that longitudinal aerodynamic resistance is a function of several important factors in underground mines: $R = f(\alpha, L, U, F)$, then, the pressure loss is the energy of the work expended on transporting a unit of mass and volume of air from one point of the mining operation to another, where this loss depends on the resistance of the conductor and the type of air movement:

$$h = \lambda \rho \frac{Lv^2}{2d} . \tag{1}$$

In mining engineering and mining aeration, for practical calculations, the air density is considered as a constant value ρ = const. Therefore, for reasons of simplifying the Formula 1, we accept a similar coefficient (α), coefficient of resistance, which is equal $\alpha = \lambda\rho / 8$; then, Expression 1 takes the form:

$$h = \alpha \frac{LU}{F} \cdot v^2 \text{, Pa.} \tag{2}$$

Considering the law of continuity, $Q = F \cdot v$, $\rightarrow v = Q / F$. Therefore, the above Equation 2 takes the form: $h = \alpha \frac{LU}{F^3} \cdot Q^2$, Pa. Then, by mathematical transformations, we obtain the basic aeration equation:

$$h = RQ^2 \text{, Pa.} \tag{3}$$

Where h (Pa) – loss of pressure (energy) to withstand aerodynamic resistances; R (kg/m^7) – aerodynamic resistance of underground mines through which air passes; Q (m^3/s) – amount of air, given or calculated according to known principles on the basis of gases or dusts released, mine productivity, number of workers, etc.

2.2. Diagonal system calculation

To select and adjust a simple diagonal system in mining engineering, the method of reciprocal resistance ratios is used, which consists in the fact that, based on the height of the resistors in the normal branches of the system and their mutual ratio, the direction of the current along the diagonal is determined, which is shown in the linear diagram (Fig. 1) [15]-[17].

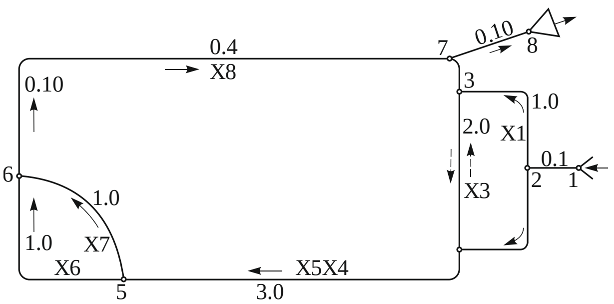

Figure 1. Linear diagram

Using the measurements presented in Table 1, the total amount of air is calculated, based on the dust released through the mine workshops and number of workers/miners, as well as from the empirical formulas:

$$Q = 1.3 \cdot k \frac{G}{n - n_0} = 71.34 \text{, m}^3\text{/s,}$$

according to the number of employees:

$$Q = k_1 nq = 30 \text{, m}^3\text{/s.}$$

Since we used different calculations and at the same time received two different values, then, for the needs of the mine, we obtained the largest value of the air amount:

$$Q = 71.34 \text{, m}^3\text{/s.} \tag{4}$$

Table 1. Dust sources according to different phases

Stope	Dust source by phases	Number of work blocks	Amount of dust release [mg/min]	Total amount of dust [mg/min]	Number of workers/ miners
X1	Drilling/ boring/hole	2	200	400 GI	10
X2	Loading-unloading	1	300	300 GII	5
X3	Drilling and stope support	2	200	400 GIII	10
X4	Automatic loading	1	300	300 GIV	5
X5	Removal	2	200	400 GV	10
X6	Removal	2	200	400 GVI	10
X7	drilling	1	250	250 GVII	5
X8	Emptying	1	250	250	5
∑	%		1900	2700	60

Based on Table 1, in which the source of dust in different phases, the number of workers, workloads and the amount of dust release are presented (Fig. 2), the total aerodynamic resistances of the system (R_e), the natural (eigen distribution) air distribution through system branches (Q_i) and main fan depression (h_v) are analyzed [18][17], [19].

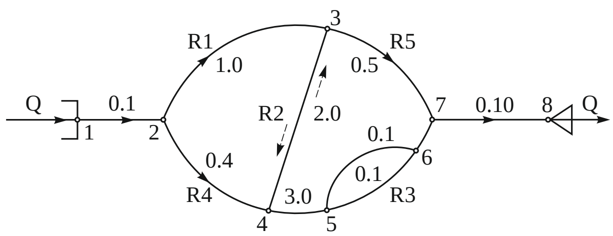

Figure 2. Canonical scheme of complex diagonal system

In order to reflect as clearly as possible in mining engineering, the canonical scheme is compiled (Fig. 2), in which all the necessary elements are marked (air inlet, branch resistances, node points and possible directions of air flow etc.). After mathematical operations, the canonical scheme (Fig. 2) is transformed (Fig. 3).

$$R_{5-6} = \frac{R_7}{\left(1 + \sqrt{\frac{R_7}{R_6}}\right)^2} = 0.25 \text{, kg/m}^7\text{;}$$

$$R_3 = R_{4-7} = R_{4-5} + R_{5-6} = 3.75 \text{, kg/m}^7\text{.} \tag{5}$$

The above mathematical Calculations 5 enable the transformation of the composite diagonal system into a simple diagonal system (Fig. 3).

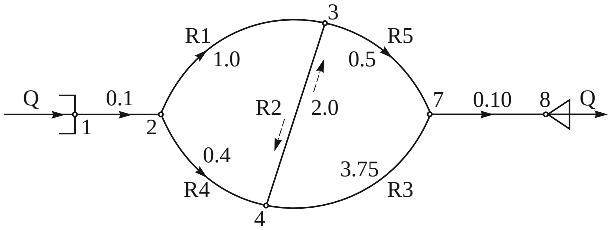

Figure 3. Transformed canonical scheme

The amount of air through the system branches is presented by the criteria of air current stability in the system, the aerodynamic resistances of the branches, the difference of branch pressures from node to node, the criterion of stability along the diagonal of the system and the mutual ratio of resistors of parallel branches: $\frac{R_1}{R_5}$ and $\frac{R_4}{R_3}$. Having analyzed the report $\frac{R_1}{R_5} > \frac{R_4}{R_3}$, we can also determine the direction of the current flow diagonally from node 4 to node 3 (Fig. 4).

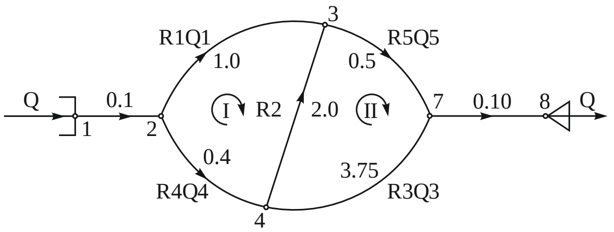

Figure 4. Canonical scheme and directions of air flow

By analogy with Figures 2 and 3, Figure 4 is obtained, in which all the necessary elements are marked, including the direction of flow along the diagonal 4 → 3.

2.3. Total system resistance

The total resistance of the system (R) is obtained from the physical legitimacy for the depression value of the system branch point. The depression value at end point 7 (Fig. 4) is the same for three different ways: 2-3-7, 2-4-7 and 2-4-3-7, if we follow the direction of current from 2 → 7. Therefore, by analogy with the Kirchhoff's second law for closed current circuits, the equations are composed:

I: $R_1Q_1^2 = R_4Q_4^2 + R_2Q_2^2$;

II: $R_3Q_3^2 = R_5Q_5^2 + R_2Q_2^2$,

or

$$\text{I: } R_1\left(\frac{Q_1}{Q_2}\right)^2 = R_2 + R_4\left(1+\frac{Q_3}{Q_2}\right)^2; \quad (6)$$

$$\text{II: } R_3\left(\frac{Q_3}{Q_2}\right)^2 = R_2 + R_5\left(1+\frac{Q_1}{Q_2}\right)^2. \quad (7)$$

After replacements: $\frac{Q_1}{Q_2} = x$ and $\frac{Q_3}{Q_2} = y$, using mathematical transformations, Equations 6 and 7 take the form:

$$\text{I: } R_1x^2 = R_2 + R_4(1+y)^2; \quad (8)$$

$$\text{II: } R_3y^2 = R_2 + R_5(1+x)^2. \quad (9)$$

Consequently, the values for x and y are:

$$x = \sqrt{\frac{R_2 + R_4(1+y)^2}{R_1}}, \quad (10)$$

and

$$y = \sqrt{\frac{R_2 + R_5(1+x)^2}{R_3}}. \quad (11)$$

Since $x = f(y)$ and $y = f(x)$, there is no exact mathematical solution, because they are functionally related, we use an approximate analytical method, which gives a satisfactory result in mining practice. In this paper, after some calculations, the most approximate values for x and y are obtained: $x = 2.041$ and $y = 1.329$.

In underground mines, the natural distribution of air through special sectors plays an important role, because better conditions are created for mining activity. Therefore, the total amount of air, calculated by Equation 4, is distributed to other branches of the system in accordance with the nature of the work. Having analyzed the canonical scheme (Fig. 4), we compose equations and, using mathematical transformations, obtain the following equations:

$$Q_2 = \frac{Q}{1+x+y}, \text{ m}^3\text{/s};$$

$$Q_3 = yQ_2, \text{ m}^3\text{/s};$$

$$Q_4 = Q_2 + Q_3, \text{ m}^3\text{/s};$$

$$Q_5 = Q_1 + Q_2, \text{ m}^3\text{/s}. \quad (12)$$

The results and patterns of natural distribution of air amount through the branches of the system according to Expressions 12 are reflected in Table 2.

Table 2. Natural air distribution

The amount of air through the branches of the system	Natural air distribution
Q_1	33.317
Q_2	16.324
Q_3	21.694
Q_4	38.018
Q_5	49.691

The total resistance of the system is obtained from the physical legitimacy in terms of the depression value at the system branch point. Therefore, the depression value at the end point 7 (Fig. 4) of the branch will be the same with any way, following the direction of air movement from the initial branch point to the end point:

1. Way: 2-4-7:

$$h_{2-7} = h_{2-4} + h_{4-7};$$

$$R_{2-7} = \frac{R_1x^2 + R_5(1+x)^2}{(1+x+y)^2} = 0.460, \text{ kg/m}^7.$$

2. Way: 2-3-7:

$$h_{2-5} = h_{2-3} + h_{3-7};$$

$$R_{2-7} = 0.460, \text{ kg/m}^7. \quad (13)$$

3. Way: 2-4-3-7:

$$h_{2-5} = h_{2-4} + h_{4-3} + h_{3-7};$$

$$R_{2-7} = 0.460, \text{ kg/m}^7.$$

Based on Figure 4 and Calculations 13 the total resistance is:

$$R_{\min} = R_{1-2} + R_{2-7} + R_{7-8} = 0.660\text{, kg/m}^7. \quad (14)$$

Based on the above calculation, it is seen that in three ways (according to the current direction) the same result is obtained, so we can determine the value of the system resistance $R = 0.660$ kg/m^7. From the total aerodynamic resistance (14) and the total amount of air (4) for the studied mine, the necessary fan depression is calculated:

$$h = R_{\min} Q^2 = 3359\text{. Pa} \quad (15)$$

3. Results and discussion

3.1. Adjustment of air conditioning

In a mine atmosphere, when supplying fresh air, we are often not satisfied with the natural air distribution, which is a consequence of the resistances existing in the system and sources of various depressions. For this purpose, the calculations are made of the air distribution in the system, in order to ensure the circulation of the required amount of air through the workshops and other mine facilities. The results of calculations by the ratio are as follows: $Q_i' = 1.3k \dfrac{G_i}{n - n_0}$, m^3/s for directed air; comparisons of natural (eigen) distribution and that of directed air for setting up ambushes are reflected in Table 3.

Table 3. Comparison of air amount for setting up ambushes

The amount of air through each branch of the system	Natural air distribution (Q_i)	Directed distribution (Qi')	Balance	Regulatory ambush
Q_1	33.316	18.495	14.821	pr_1
Q_2	16.324	10.569	5.755	pr_2
Q_3	21.694	42.276	-20.582	
Q_4	38.018	52.845	-14.827	
Q_5	49.641	29.064	20.577	pr_5

Comparison of the natural distribution (Q_i) and directed distribution (Qi') results in Table 3 shows that in all branches of the system (Fig. 5), with calculated resistances (R_i), in which a larger amount of air passes than it is necessary, we set adjusting barriers (pr_i) with aerodynamic resistance (re) in order to pass the directed amount of air (Qi').

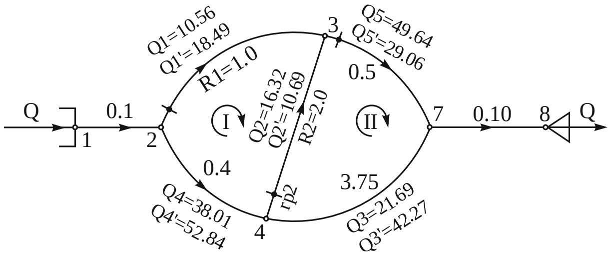

Figure 5. Canonical scheme with regulating ambushes

Based on Figures 5 and the applied principle of regulating the aerodynamic resistance of the system branches through which air must pass (New + new), for all routes of the ventilation system, from point 2 at the inlet to point 7 at the outlet through which the air passes, the equations of the following type are composed:

$$r_{p1}Q_1'^2 + R_1 Q_1'^2 - r_{p2}Q_2'^2 - R_2 Q_2'^2 - R_4 Q_4'^2 = 0\,; \quad (16)$$

$$r_{p2}Q_2'^2 + R_2 Q_2'^2 + r_{p5}Q_5'^2 + R_5 Q_5'^2 - R_3 Q_3'^2 = 0\,. \quad (17)$$

Since the maximum resistance is obtained in the 2-4-3-7 ways, then, according to the principle of ventilation of mines along the diagonal, there is no need to adjust the ambush, so we accept $r_2 = 0$. Therefore, Expressions 16 and 17 after mathematical transformations have the form:

$$r_{p1} = \frac{R_2 Q_2'^2 + R_4 Q_4'^2 - R_1 Q_1'^2}{Q_1'^2} = 2.91\text{, kg/m}^7; \quad (18)$$

$$r_{p5} = \frac{R_3 Q_3'^2 - R_5 Q_5'^2 - R_2 Q_2'^2}{Q_5'^2} = 7.17\text{ , kg/m}^7. \quad (19)$$

These regulators are additional resistances in the embedded branches of the system, therefore, based on the expression ($R_i + r_i$), the resistance of the branch, which is placed in the ambush, is obtained:

$$r_{p5} = \frac{R_3 Q_3'^2 - R_5 Q_5'^2 - R_2 Q_2'^2}{Q_5'^2} = 7.17\text{ , kg/m}^7.$$

$$R_1' = R_1 + r_{p1} = 3.91\text{, kg/m}^7; \quad (20)$$

$$R_5' = R_5 + r_{p5} = 7.67\text{ , kg/m}^7. \quad (21)$$

While the ratio of air amount is calculated based on the expression, $x_i = \dfrac{Q_i'}{Q}$ it follows that:

$$x_1' = \frac{Q_i'}{Q} = 0.259\,, \quad x_2' = 0.148\,, \quad x_3' = 0.592\,,$$

$$x_4' = 0.740\,, \quad x_5' = 0.407\,. \quad (22)$$

After these calculations, the canonical scheme (Fig. 5) is transformed as shown in Figure 6, which reflects the new resistances.

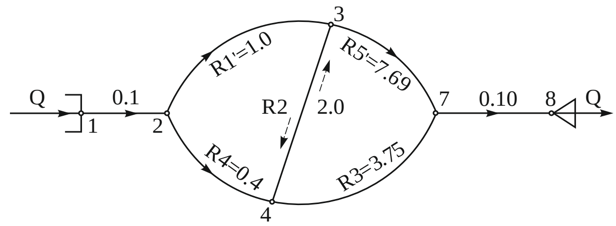

Figure 6. Canonical scheme after laying ambushes

The new resistors (R'_1 and R'_5) are presented in Figure 6, where even after adjustment the direction of current along the diagonal is $3 \rightarrow 4$. This means that the resistance value along the diagonal does not play a role in the direction of air flow in it. Therefore, based on the analogy of Expressions 8 and 9, after placing the dams, the new roots can be calculated:

$$x' = \sqrt{\frac{R_2 + R_4\left(1 + y'\right)^2}{R_1'}} \text{ and } y' = \sqrt{\frac{R_2 + R_5'\left(1 + x'\right)^2}{R_3}}\,. \quad (23)$$

After some analytical calculations with approximate values of x and y, $x' = 1.75$ and $y' = 4.0$ are obtained.

Even after adjusting the system, system resistances are achieved from physical legitimacy of the depression value at the system branch point. Thus, the depression value at end point 7 (Fig. 6) of the branch remains the same with any way, always following the direction of air movement from the initial branch point to the end point:

1. Way: 2-3-7:

$$R' = R'_{2-7} = \frac{R'_1 x'^2 + R'_5 (1+x')^2}{(1+x'+y')} = 1.535 \text{, kg/m}^7. \quad (24)$$

2. Way: 2-3-7:

$$R' = R'_{2-7} = \frac{R_3 y'^2 + R_4 (1+y')^2}{(1+x'+y')} = 1.536 \text{, kg/m}^7. \quad (25)$$

3. Way:2-3-4-7:

$$R' = R'_{2-7} = \frac{R_4 (1+y')^2 + R_2 + R'_5 (1+x')^2}{(1+x'+y')^2} = 1.536 \text{, kg/m}^7. \quad (26)$$

In mathematical analogies:

$$R_{\min} = R_{1-2} + R'_{2-7} + R_{7-8} = 1.736 \text{, kg/m}^7. \quad (27)$$

According to the total aerodynamic resistance 27 and the total amount of air (4), the required fan depression, equivalent hole and electric motor power are calculated:

$$h'_v = R' \cdot Q^2 = 8836 \text{, Pa.} \quad (28)$$

Equivalent hole:

$$A = \frac{1.2Q}{h'_v} = 0.91 \text{, m}^2. \quad (29)$$

Electric motor power:

$$N' = \frac{Qh'_v}{\eta_v} = 971.36 \text{, kW.} \quad (30)$$

Where η_v = 0.65 – ventilator utilization coefficient.

The results obtained and reflected in Table 4 are used to construct a potential scheme (Fig. 7) of the aeration system, which represents the decrease in isochoric potential for (ρ = const).

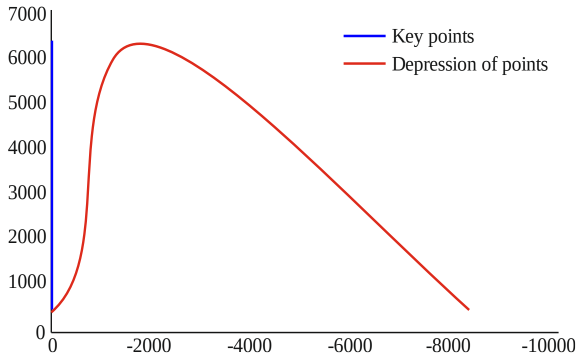

Figure 7. Potential/possible scheme

Table 4 reflects the depression values of the system branches by tracing the direction of air flow from point 1 to point 8, aerodynamic resistances, air volumes of each branch and each branch depressions. This also confirms that with the accuracy at point 8, the same depression values are acquired in all possible ways.

The potential/possible diagram (Fig. 7) contains the position of the fans in the system, the direction of the air currents, the key points of the system, as well as the data on the depression values between the points of the system.

Table 4. Depression values of system branches

Branch	Resistance "*R*"	Amount of air "*Q*"	Depression "*h*"
1-2	0.10	71.34	508.94
2-4	0.40	52.845	1117.04
4-7	3.75	42.276	6702.23
4-3	2.00	10.569	223.41
2-3	3.91	18.50	1340.45
3-7	7.67	29.06	6478.82
7-8	0.10	71.34	508.94
Way: 1-2-4-7-8			
Branch	The decline of depression	Key points	Depression point
1-2	508.94	1	0
2-4	1117.04	2	-508.94
4-7	6702.23	4	-1625.98
7-8	508.94	7	-8328.20
		8	-8837.14
Way: 1-2-4-3-7-8			
Branch	The decline of depression	Key points	Depression point
1-2	508.94	1	0
2-4	1117.04	2	-508.94
4-3	223.41	4	-1625.98
3-7	6478.82	3	-1849.38
7-8	508.94	7	-8328.20
		8	-8837.14
Way: 1-2-3-7-8			
Branch	The decline of depression	Key points	Depression point
1-2	508.94	1	0
2-3	1340.45	2	-508.94
3-7	6478.82	3	-1849.38
7-8	508.94	7	-8328.20
		8	-8837.14

4. Conclusions

After detailed analysis and calculation of the simple diagonal system we conclude.

The importance of adjusting the simple diagonal system regarding the problem of ventilation of underground mines includes determining aerodynamic resistances, the amount of air passing through all system branches, the direction of flow along the diagonal of the system, as well as other important parameters that are submitted to design tasks, such as a sufficient amount of air in accordance with safety regulations. The purpose of using different regulators is to reduce by a certain value the amount of air through certain ways or even in different parts of the mine, as well as take it to the other side of the mine. Therefore, for this purpose, we have used a regulation with adjusting ambushes, which in most cases is called as a negative regulation. Because in this way the aerodynamic resistances and the fan pressure necessary to withstand them increase, which negatively affects the ventilation efficiency.

For the studied case, it can be seen that before setting the ambushes, the following results have been obtained: R_{2-7} = 0.460 kg/m^7; $R_{\min}$ = 0.660 kg/m^7; N_v = 368.66 kw; h_v = 3359 Pa, while regulatory expectations have completely changed these values, increasing them by 2-3 times: R'_{2-7} = 1.535 kg/m^7; $R'_{\min}$ = 1.736 kg/m^7; N'_v = 971.36 kw; h'_v = 8836 Pa.

In mining engineering, between these costs in the implementation of regulation and the consumption of electricity after regulation, it is always necessary to look for ratios that lead to the optimal solution.

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Ефективність регулювання вентиляції в простій діагональній системі підземних шахт

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Мета. Проведення порівняння результатів безпеки, які вказують на реальний стан мікроклімату в підземних гірничих виробках, що впливає на підвищення перспектив розвитку гірничодобувної діяльності.

Методика. У цій роботі розглядається проблема вентиляції в підземних шахтах, особливо в діагональних системах, а також важливість регулювання вентиляції для забезпечення необхідної кількості повітря (Q, м^3/хв) через всю систему з урахуванням визначення депресії головного вентилятора. Для досягнення мети визначались аеродинамічні опори, кількість повітря, що проходить через всі відгалужуючі системи, напрямки потоку в діагоналі системи та інших важливих параметрів відповідно до правил техніки безпеки.

Результати. Доведено, що для забезпечення необхідної (проєктної) кількості повітря через відгалуження системи в гірничотехнічній галузі можуть застосовуватись різні методи ефективного регулювання. Встановлено, що на основі досліджень та вимірювань у різних гірничих виробках, проведені розрахунки можуть забезпечити повну безпеку та комфорт мікроклімату під час гірничих робіт.

Наукова новизна. Створено нову базу даних параметрів вентиляційної системи на основі значень та результатів, отриманих при аналітичних розрахунках та проведених вимірюваннях, що дозволяє знайти оптимальне рішення.

Практична значимість. Вирішено задачу розрахунку та регулювання аерації для простої діагональної системи з урахуванням визначення депресії основного шахтного вентилятора до та після застосування регуляторів аерації.

Ключові слова: *об'єм повітря, вентиляційна система, регулювальні пристрої, аеродинамічний опір, вентилятор, шахта*