fire

Article

Modeling and Complex Analysis of the Topology Parameters of Ventilation Networks When Ensuring Fire Safety While Developing Coal and Gas Deposits

Igor Ivanovich Bosikov [1], Nikita V. Martyushev [2,*], Roman V. Klyuev [3], Irina A. Savchenko [4,5], Vladislav V. Kukartsev [6,7,8], Viktor A. Kukartsev [9] and Yadviga A. Tynchenko [10,11]

1 Department of Information Technologies and Systems, North Caucasian Institute of Mining and Metallurgy, State Technological University, 44, Nikolaev Str., 362011 Vladikavkaz, Russia
2 Department of Advanced Technologies, Tomsk Polytechnic University, 30, Lenin Ave., 634050 Tomsk, Russia
3 Technique and Technology of Mining and Oil and Gas Production Department, Moscow Polytechnic University, 33, B. Semenovskaya Str., 107023 Moscow, Russia
4 Department of Philosophy and Social Sciences, Moscow City University, 129226 Moscow, Russia
5 International Laboratory "Research Methods in Social Science", Linguistics University of Nizhny Novgorod, 603155 Nizhny Novgorod, Russia
6 Department of Information Economic Systems, Institute of Engineering and Economics, Reshetnev Siberian State University of Science and Technology, 660037 Krasnoyarsk, Russia
7 Department of Informatics, Institute of Space and Information Technologies, Siberian Federal University, 660041 Krasnoyarsk, Russia
8 Digital Material Science: New Materials and Technologies, Bauman Moscow State Technical University, 105005 Moscow, Russia
9 Department of Materials Science and Materials Processing Technology, Polytechnical Institute, Siberian Federal University, 660041 Krasnoyarsk, Russia
10 Laboratory of Biofuel Compositions, Siberian Federal University, 660041 Krasnoyarsk, Russia
11 Department of Systems Analysis and Operations Research, Reshetnev Siberian State University of Science and Technology, 660037 Krasnoyarsk, Russia
* Correspondence: martjushev@tpu.ru

Abstract: Underground mining, including underground coal mining, is accompanied by accidents and fire hazards that pose a threat to the life safety of miners. The fire hazard increases with an increase in the mining depth. Currently, most accidents in coal mines are mine fires. The cost of eliminating mine fires is 80–95% of the cost of eliminating all accidents occurring at mining enterprises. Therefore, the problem of developing a new methodology for modeling the ventilation network parameters of the mine to increase the reliability of controlling the aerogas mode at the excavation site is very relevant. The comprehensive analysis and assessment of gas-dynamic processes in coalmines under study were carried out using the methods of probability theory and mathematical statistics. Spatial data were processed using spline interpolation in "gnuplot". As a result, a generalized expression for the transfer functions of coalmine objects, taking into account delays, was developed, including the description of dynamic properties of mining sites under various operating modes. The principal possibility of using a graphical method for estimating additional parameters of the sections of the ventilation system branches has been proved due to the alignment of their profiles at an equivalent distance relative to an arbitrary analogue. The improved method of spatial modeling was used to determine the gas-dynamic characteristics through additive gas-dynamic processes. The studies have been carried out and the method for managing the process of changing connections between devices (controllers–switches) of the technical system was developed in order to obtain greater reliability for safe mining. In subsequent studies, there is an issue of more detailed clarification of the peculiarities concerning the interrelations between the studied parameters in several projections of the response space.

Keywords: coal mine; coal bed methane; fires; explosion safety

Citation: Bosikov, I.I.; Martyushev, N.V.; Klyuev, R.V.; Savchenko, I.A.; Kukartsev, V.V.; Kukartsev, V.A.; Tynchenko, Y.A. Modeling and Complex Analysis of the Topology Parameters of Ventilation Networks When Ensuring Fire Safety While Developing Coal and Gas Deposits. *Fire* **2023**, *6*, 95. https://doi.org/10.3390/fire6030095

Academic Editors: Haiyan Wang, Feng Li, Huiyong Niu, Minbo Zhang and Xuyao Qi

Received: 26 January 2023
Revised: 18 February 2023
Accepted: 28 February 2023
Published: 1 March 2023

1. Introduction

Underground mining, including underground coal mining, is accompanied by the danger of arising emergencies and fire hazards that pose a threat to the life safety of miners [1–3]. The development of mining enterprises implies the complication of mining-geological and mining conditions: an increase in the depth of mining operations, natural gas content of coal seams, depletion of highly productive reserves, etc. Increasing the depth of mining operations leads to the intensification of negative manifestations of mountain pressure, the appearance of new zones of spontaneous combustion [4,5] and an increase in the frequency of appearance of gas dynamic phenomena [6,7]. In addition, there are new difficulties in ensuring the explosion safety of mining reserves following the disruption of the local degassing network operation as a result of: a loss in the stability of underground wells [8,9], crumpling of casing pipes [10], spacing of the main roof breaks [11] imperfections in well parameters [12,13], and fire hazards in pipelines [14].

The issues of fire hazard are sufficiently detailed in [15–17], reflecting the results of studies on the influence of water erosion on the fire hazard of a coal dump [18], on using indicator gas [19] in fire detection, and analysis of the impact of fires in coal mines on carcinogenic and non-carcinogenic risks to human health [20]. Based on the predictive analysis, the authors concluded that in order to ensure the fire-safe condition of mining sites, it is necessary to develop a system for monitoring the release of methane and other explosive gases using modern multifunctional safety systems [21,22]. It is also necessary to develop a set of measures for designing coal lavas in severe mining and geological conditions [23,24] in coalmines.

The expenditures on eliminating mine fires account for 80–95% of the costs of eliminating all the accidents at mining enterprises [25,26]. Among the main causes of endogenous fires, the following should be singled out: spontaneous combustion of coal dust; absence of preventive treatment (silting) of the mined-out space; opening and preparation of the excavation site in violation of the requirements regarding the laying of the ventilation scheme. They also include violation of the lava attachment passport; insufficiently high efficiency of preventive treatment of the formation; insufficient organization of the work of the control and monitoring service of the ventilation and safety rules (SR); oxidation of a coal slack in conditions of weak ventilation that is insufficient for removing thermal energy from the oxidation zone. A number of the following measures are proposed to be used as methods of control. These are the use of steel structures with intumescent [27], the methodology of fire dynamics in mine workings [28], increasing the role of complex assessment of hidden hazards based on data mining [29], improving the methods of modeling the spread of smoke [30], and evolution of methane explosion foci [31], including using estimates of time series of data [32]. At the same time, it is necessary to determine the boundaries of the optimal state of gas-dynamic processes and adapt the methodology at coal industry enterprises [33,34]. At the same time, it is of great importance to choose a rational period for extracting the information received from the controlled objects [35,36], as well as comprehensive monitoring of cause-and-effect relationships leading to accidents [37,38] and methods of liquidating underground fires [39].

Therefore, it can be argued that there is a contradiction between the needs of practice and the possibilities of theory. Within the framework of the theory, there is currently no consideration of issues on the use of complex analysis and monitoring of cause-and-effect relationships. They lead to accidents associated with methane emissions for effective prevention of safe mining operations in the coalmines. The improvement of the methodology for modeling the parameters of the ventilation network of the mine to increase the reliability of controlling the aerogas mode at the excavation site (in case of instability in the methane release dynamics) is a very relevant scientific problem. Its solution will allow improving the safety of mining operations in coal lavas.

The purpose of this work is to develop a new approach to analyzing the topology parameters of ventilation networks while ensuring the fire safety of the development of coal and gas deposits.

2. Materials and Methods

The solution of the set tasks is based on modern methods of mathematical statistics, decision theory, probability theory, method of active experiment and system analysis, and methodology for assessing aerologic risks [40,41].

To achieve the goal of reducing the fire and explosion hazard of the coal mining process [5], the authors used the method of the active experiment. The method was used to determine the measurement interval Δt_{β}. For this purpose, the dependence between the limit function $I_C^*(\Delta t)$ and the transition function $h_C(\Delta t)$ of the methane concentration was established.

Mine 31 was chosen as an object of studying the aerogas-dynamic parameters of the topology of the mine workings, which is part of the Sadkinsky coal deposit. It is located on the border of two districts, Ust-Donetsky and Belokalitvinsky. Coal has been mined on the territory of the latter for a long time. The total reserves of the deposit are about 300 million tons. The estimated bottomhole depth is 350 m at mine 31. The design capacity of the mine is three million tons of coal per year. At the first stage, one face is planned to be exploited, which is expected to provide one and a half million tons of anthracite annually.

The main hypothesis of the study was the provision on the possibility of using a graphical method for evaluating additional parameters of sections of branches of the ventilation network owing to building their profiles with an equivalent remoteness relative to an arbitrary analogue (a maximally extended branch) and the direction of reporting. This approach is based on the need to consider the scheme of the branches of the ventilation network in a three-dimensional space (a four-dimensional problem). Its obtainment is possible if there are two projections of the network topology (for example, frontal and profile), which in turn will allow more reliable control of air distribution in the working area to ensure the fire safety of mining operations. To process the scattered data of the ventilation network parameters, spline interpolation was used in the "gnuplot" program [10,42].

3. Results and Discussion

3.1. The Interrelation between the Transition Function of the Methane Concentration and the Functional of the Influencing Parameters of the Ventilation Network Topology

Let a non-stationary discrete sequence of methane concentration values $C(t_k)$, $t_k = t_{\overline{k}1} + \Delta t$ be obtained during the normal operation of the facility on the observation section $(0, t)$, where Δt is the selected discreteness interval ($\Delta t = const$, K = 1, 2, 3, …). It is required to find such functionality I_C that should not exceed the value of the safety criterion β over the time interval between two adjacent measurements of the methane concentration [43]. Having proceeded through the entire discrete sequence $C(t_k)$ for values $K = 1, 2, 3, \ldots$, let us find the maximum value of the functional $I_C^*(\Delta t)$ for the selected discreteness interval Δt and express it through the parameters of the transient gas dynamic process $h_C(t)$.

It is known that in case of an arbitrary input action $X(t)$ on a link with an impulse function $K(t)$, the reaction of the link at time t is equal to [44]:

$$Y(t) = \int_0^t K(t-\tau)X(\tau)\,d\tau. \tag{1}$$

Let us consider the technical system of the mining site as a control object with a known impulse function $K_C(t)$. The transient process of the methane concentration $h_C(t)$ (the transient gas-dynamic process is represented as deviations from the steady-state mode, which allows the increasing of the accuracy of determining the dynamic characteristics of ventilation objects by transient gas-dynamic processes), caused by the controlling action of the air flow $Q(t)$ of an arbitrary shape at time t, will be equal to:

$$h_c(t) = \int_0^t K_c(t-\tau)Q(t)dt, \tag{2}$$

where τ is an implementation shift interval, min.

Let us write expressions for the transient process $h_C(t)$ at time t_1 and t:

$$h_c(t) = \int_0^{t_1} K_c(t_1-\tau)Q(\tau)d\tau, \tag{3}$$

$$h_c(t) = \int_0^{t_2} K_c(t_2-\tau)Q(\tau)d\tau. \tag{4}$$

The difference of the two integrals in Expressions (3) and (4) will be equal to the increment of the transition process $h_C(t)$ on a time segment $\Delta t = t_2 - t_1$:

$$h_c(\Delta t) = h_c(t_2) - h_c(t_1) = \int_0^{t_2} K_c(t_2-\tau)Q(\tau)d\tau - \int_0^{t_1} K_c(t_1-\tau)Q(\tau)d\tau. \tag{5}$$

Considering the fact that $k(t_1-\tau)$ when $\tau > t_1$, let us write Expression (5) in the form of a single integral:

$$h_c(\Delta t) = \int_0^{t_1+\Delta t} K_c(t_1+\Delta t-\tau)K_c(t_1-\tau)Q(\tau)d\tau. \tag{6}$$

The determination of the maximum possible increment of the methane concentration $C(t)$ is reduced to the problem of maximization on the segment $(t; t+\Delta t)$ by the variables Q and t of the integral in Expression (6):

$$I_c^*(\Delta t) = \max h_c(\Delta t) = \max \int_0^{t+\Delta t} K_c(t+\Delta t-\tau)K_c(t-\tau)Q(\tau)d\tau. \tag{7}$$

In this expression, the index of the variable t is omitted and it is assumed that the function $Q(t)$ changes within 0.1. In this way, the problem under consideration is reduced to determining, in case of a preset impulse function $K_c(\tau)$ and a fixed measurement interval Δt, the measurement of the type of control action $Q(\tau)$ that provides the maximum value of the transition process $h_C(\Delta t)$. To solve (7), let us make the following substitution $t+\Delta t-\tau = \varepsilon$; then:

$$K_c(t+\Delta t-\tau) - K_c(t-\tau) = P(\varepsilon, \Delta t). \tag{8}$$

Then, the maximized integral will take the form:

$$\int_0^{t_1+\Delta t} P(\varepsilon, \Delta t)Q(t+\Delta t-\varepsilon)d\varepsilon. \tag{9}$$

where

Q is the air consumption on the segment $(t + \Delta t - \varepsilon)$;

t_1 is the measuring time at point 1;

Δt is the discreteness interval, fixed interval;

ε is the measurement error of air flow and methane flow rate;

P is the probability of falling into the extreme quantum of the range ε, Δt.

The maximum value of this integral is achieved in the case of (a):

$$Q(t + \Delta t - \varepsilon) = signP(\varepsilon, \Delta t), \tag{10}$$

where

$$sign\begin{cases} 0\, when\; P \le 0 \\ I\, when\; P > 0 \end{cases}. \tag{11}$$

As well as in the case of (b):

$$Q(t + \Delta t - \varepsilon) = \bar{s}ignP(\varepsilon, \Delta t), \tag{12}$$

where

$$\bar{s}ign\begin{cases} 0\, when\; P \le 0 \\ I\, when\; P \ge 0 \end{cases}. \tag{13}$$

Therefore, taking into account (10) and (12), let us obtain:

$$I_1(\Delta t, t) = \int_0^{t+\Delta t} P(\varepsilon, \Delta t)\, \bar{s}ignP(\varepsilon, \Delta t)\, d\varepsilon; \tag{14}$$

$$I_2(\Delta t, t) = \int_0^{t+\Delta t} P(\varepsilon, \Delta t)\, signP(\varepsilon, \Delta t)\, d\varepsilon. \tag{15}$$

Integrals (14) and (15), being functions of the variable t, reach a maximum when $t = +\infty$ at any Δt. Consequently, the maximum of the considered integral is also achieved when $t = +\infty$:

$$I_c^*(\Delta t) = \max\{I_1(\Delta t, \infty), I_2(\Delta t, \infty)\} \tag{16}$$

The difference of the functions $I_1(\Delta t, t)$ and $I_2(\Delta t, t)$ when $t = +\infty$ is equal to:

$$I_1(\Delta t, \infty) \; - I_2(\Delta t, \infty) = \int_0^{\infty} P(\varepsilon, \Delta t)\, [signP(\varepsilon, \Delta t) + \bar{s}ignP(\varepsilon, \Delta t)\,]d\varepsilon = \int_0^{\infty} P(\varepsilon, \Delta t) d\varepsilon = 0. \tag{17}$$

where $signP(\varepsilon, \Delta t) + \bar{s}ignP(\varepsilon, \Delta t) = 1$.

The integral in the Expression (17) is zero since the function $P(\varepsilon, \Delta t)$ is the difference of two identical functions, the argument of one of which is ahead of the other by the value Δt and at the initial interval $(0, \Delta t)$ due to the ratio $k(t - \tau) \le 0$. When $\tau > t$, this function is also equal to zero.

The equality of the functions follows from the last expression $I_1(\Delta t, t)$ and $I_2(\Delta t, t)$.

The maximum of the integral under consideration is reached at the time $t = +\infty$, when the control variable changes abruptly:

$$Q(t) = sign\; [K_c(t + \Delta t - \tau) K_c(t - \tau)] = signP \tag{18}$$

where $sign\begin{cases} 0\, when\; P \le 0 \\ I\, when\; P \ge 0 \end{cases}.$

Let us further consider the case when the impulse function $K_c(\varepsilon)$ is a positive monotonically decreasing function.

Let us write the function $I_C^*(\Delta t)$ in the form of:

$$I_C^*(\Delta t) = \int_0^{\infty} [K_c(\varepsilon) - K_c(\varepsilon - \Delta t)] \cdot signP(\varepsilon, \Delta t) d\varepsilon. \tag{19}$$

Let us transform Expression (19) as follows:

$$\begin{gathered} I_C^*(\Delta t)=\int\limits_0^t[K_c(\varepsilon)-K_c(\varepsilon-\Delta t)]\cdot signP(\varepsilon,\Delta t)d\varepsilon+\int\limits_{\Delta t}^{\infty}[K_c(\varepsilon)-K_c(\varepsilon-\Delta t)]\cdot signP(\varepsilon,\Delta t)d\varepsilon= \\ =\int\limits_0^{\Delta t}K_c(\varepsilon)\cdot signP(\varepsilon,\Delta t)d\varepsilon-\int\limits_0^{\Delta t}K_c(\varepsilon-\Delta t)\cdot signP(\varepsilon,\Delta t)d\varepsilon+\int\limits_{\Delta t}^{\infty}[K_c(\varepsilon)-K_c(\varepsilon-\Delta t)]\cdot signP(\varepsilon,\Delta t)d\varepsilon \end{gathered}. \quad (20)$$

The integrals in Expression (20) are as follows:

$$\int\limits_0^{\Delta t}K_c(\varepsilon-\Delta t)\cdot signP(\varepsilon,\Delta t)d\varepsilon=0; \quad (21)$$

$$\int\limits_{\Delta t}^{\infty}[K_c(\varepsilon)-K_c(\varepsilon-\Delta t)]\cdot signP(\varepsilon,\Delta t)d\varepsilon=0. \quad (22)$$

In Formula (21), the impulse function $K_c(\varepsilon-\Delta t)=0$ is on the segment $(0,\Delta t)$, and in Formula (22), due to the monotony of the function $K_c(\varepsilon)$, the difference of the functions $K_c(\varepsilon)-K_c(\varepsilon-\Delta t)$ is everywhere on the interval $t=+\infty$; therefore, $signP(\varepsilon,\Delta t)\geq 0$.

The integral $\int\limits_0^{\Delta t}K_c(\varepsilon)\cdot d\varepsilon$ in the Formula (20) represents the value of the required one $h_C(t)$, while the function $I_C^*(\Delta t)$ is identically equal to it (which was to be proved):

$$I_C^*(\Delta t)=h_c(t) \quad (23)$$

As a result, it has been proved that the impulse function is a monotonically decreasing non-negative one only in case of an abrupt decrease in the air flow at the site. Consequently, the transient gas-dynamic processes, obtained when the air flow decreases abruptly, are identically equal to the function $h_C(t)$ and can be used to determine the interval of measurement through the safety criterion β.

3.2. The Relationship between the Change of the Air Flow in the Working Area and the Transition Function of the Methane Concentration

To determine the maximum increment in the consumption of the air required to obtain the transient process $h_C(t)$, it is necessary to determine the relationship between the air rates before and after changing the gas release at the site, ensuring the methane concentration at the level C^* (methane concentration value, CH_4, m^3/min).

In previous studies, it has been found [45] that when gas is released at the site q, the required air consumption value is $Q=\frac{q_1}{C^*}$. Let us assume the fact that in the case of the known level of gas release at the site, the actual flow rate Q_1 differs from the required level Q, and the actual methane concentration C differs from C^*. Then, we have the expression $C=\frac{q_1}{Q_1}$ for the case of non-optimal control of the aerogas mode at the site.

Now the final expression (when dividing $\frac{Q}{Q_1}$) to determine the required flow rate will take the form:

$$Q=\frac{C}{C^*}Q_1. \quad (24)$$

Considering the fact that the methane concentration C satisfies the ratio:

$$C<C_p>C^*+\beta$$

where C_p is the level regulated by the "Safety Rules for coal mines" of the district.

β is the safety criteria by the ventilation factor (0.2–0.4% of methane in the air jet coming from the working area).

After substituting the value of C into the expression (24), we obtain:

$$Q = \frac{C^* + \beta}{C^*} Q_1 \tag{25}$$

The final increment of the air consumption rate, which must be supplied to the site to obtain a transient gas-dynamic process $h_C(t)$, will take the form:

$$Q = (0.5 + 0.66) Q_1 \tag{26}$$

As a result, the boundary ranges of the aerologic parameters of the ventilation network of the mine were established to control situational changes in the level of methane release in the working area.

3.3. Assessment of the Aerogas-Dynamic Parameters of the Topology of Mine Workings at Mine 31

The scheme of air connections of the inclined panel 18-P, mine 31 is shown in Figure 1. It is referred to complex diagonal connections (42 diagonals, or 89.3% of the total number of mine branches). The parameters of the air connections are shown in Table 1.

Table 1. Indicators of the aerogas-dynamic parameters of the typical diagram.

Branch	Parameters			Branch	Parameters			Branch	Parameters		
	R, kμ	Q, m^3/s	h, Pa		R, kμ	Q, m^3/s	h, Pa		R, kμ	Q, m^3/s	h, Pa
1–3	0.0004	60.03	1.44	62–74	0.0018	39.85	2.86	69–71	0.0605	2.78	9.88
3–5	0.0013	59.59	4.62	22–26	0.1	10.41	1.08	71–73	0.0054	9.92	0.53
5–7	0.00313	35.12	3.86	30–34	0.01	2.88	0.08	71–75	0.066	2.07	0.28
7–9	0.0005	34.73	0.6	46–50	0.0025	0.52	0.0007	75–73	0.0895	1.87	0.2
9–11	0.00313	6.59	0.14	62–66	0.0025	2.07	0.01	73–14	0.2919	11.58	39.16
11–13	0.005	6.19	0.019	13–22	800	0.27	59.71	14–16	0.0044	23.69	2.47
13–17	0.00363	5.92	0.13	17–30	88.888	0.84	62.39	47–10	350	0.39	52.31
17–25	0.00726	5.07	0.19	25–46	43.75	1.24	67.28	49–20	50	0.87	38.05
25–33	0.00726	3.83	0.11	33–62	37.5	1.39	72.44	45–61	0.0011	13.49	0.20
33–37	0.004	2.45	0.02	37–76	350	0.46	75.62	61–63	0.0605	12.89	10.05
37–74	19.05	1.99	75.27	5–39	0.0075	24.47	4.49	63–65	0.0054	10.01	0.54
74–76	0.0002	41.84	0.35	39–41	0.0039	22.96	0.65	63–67	0.066	2.08	0.29
76–78	0.0002	42.30	0.36	41–43	0.0021	12.56	0.33	67–65	0.0895	1.89	0.26
1–18	3.19	4.20	56.23	43–84	0.2455	11.60	33.06	65–12	0.2925	11.7	40.05
18–20	0.0194	5.14	0.51	84–86	0.0635	12.80	10.4	12–14	0.0066	12.08	0.96
20–26	0.435	6.01	15.70	86–6	0.0623	13.41	11.21	69–86	100	0.6	36.31
26–34	0.0067	16.42	1.81	6–8	0.0044	27.10	3.23	71–84	25	0.8	16.01
34–50	0.0134	19.31	5.0	41–2	350	0.41	58.23	75–84	100	0.4	15.73
50–66	0.0134	19.84	5.27	43–18	50	0.94	44.7	61–82	100	0.6	36.04
66–78	0.0074	21.93	3.56	39–80	0.2412	11.50	31.92	63–80	25	0.79	15.76
3–2	350	0.44	67.99	80–82	0.0635	12.69	10.23	67–80	100	0.39	15.48
2–8	0.0014	0.85	0.001	82–4	0.1694	13.29	12.26	11–12	350	0.4	56.64
8–10	0.00023	27.95	0.18	4–6	0.0066	13.69	1.24	22–30	0.0016	41.88	2.81
10–16	0.0004	28.33	0.222	7–4	350	0.40	55.04	45–47	0.0039	14.65	0.84
16–22	0.00023	52.04	0.62	9–45	0.0075	28.14	5.94	30–46	0.0032	39.84	5.08
47–49	0.0021	14.26	0.43	46–62	0.0032	40.55	5.26	49–69	0.00535	13.39	0.96

To implement the general research methodology, equidistant sections of the three branches (extreme right = 1; extreme left = 2 and the subsequent left following it = 3) were classified relative to the right branch with 13 sections (Table 2).

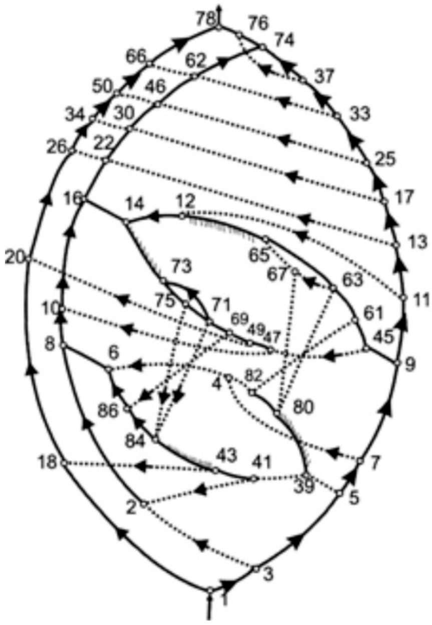

Figure 1. Schematic representation of the ventilation network at mine 31, divided into components of the limited complexity.

Table 2. Aggregated network parameters taking into account the projection of the sphere on a horizontal plane.

Branch Number	Number of the Section of the Same Length	Sections on the Diagram (Figure 1)	*Q*	*R*
(M)	(N)		m^3/s	kμ
1	1	1–3	60.03	0.0004
1	2	3–5	59.59	0.0013
1	3	5–7	35.12	0.00313
1	4	7–9	34.73	0.0005
1	5	9–11	6.59	0.00313
1	6	11–13	6.19	0.005
1	7	13–17	5.92	0.00363
1	8	17–25	5.07	0.00726
1	9	25–33	3.83	0.00726
1	10	33–37	2.45	0.004
1	11	37–74	1.99	19.05
1	12	74–76	41.84	0.0002
1	13	76–78	42.3	0.0002
2	3	1–18	4.2	3.19
2	6	18–20	5.14	0.0194
2	8	20–26	6.01	0.435
2	9	26–34	16.42	0.0067
2	10	34–50	19.31	0.0134
2	12	50–66	19.84	0.0134
2	13	66–78	21.93	0.0074
3	2	3–2	0.44	350
3	4	2–8	0.85	0.0014
3	5	8–10	27.95	0.00023
3	7	10–16	28.33	0.0004
3	8	16–22	52.04	0.00023
3	9	22–30	41.88	0.0016
3	9.5	30–46	39.84	0.0032
3	10	46–62	14.26	0.0021
3	11	62–74	39.85	0.0018

Using modern means of three-dimensional interpolation when processing the data from Table 2, by analogy with [46,47], let us obtain separate response surfaces for *Q* and *R* (Figure 2).

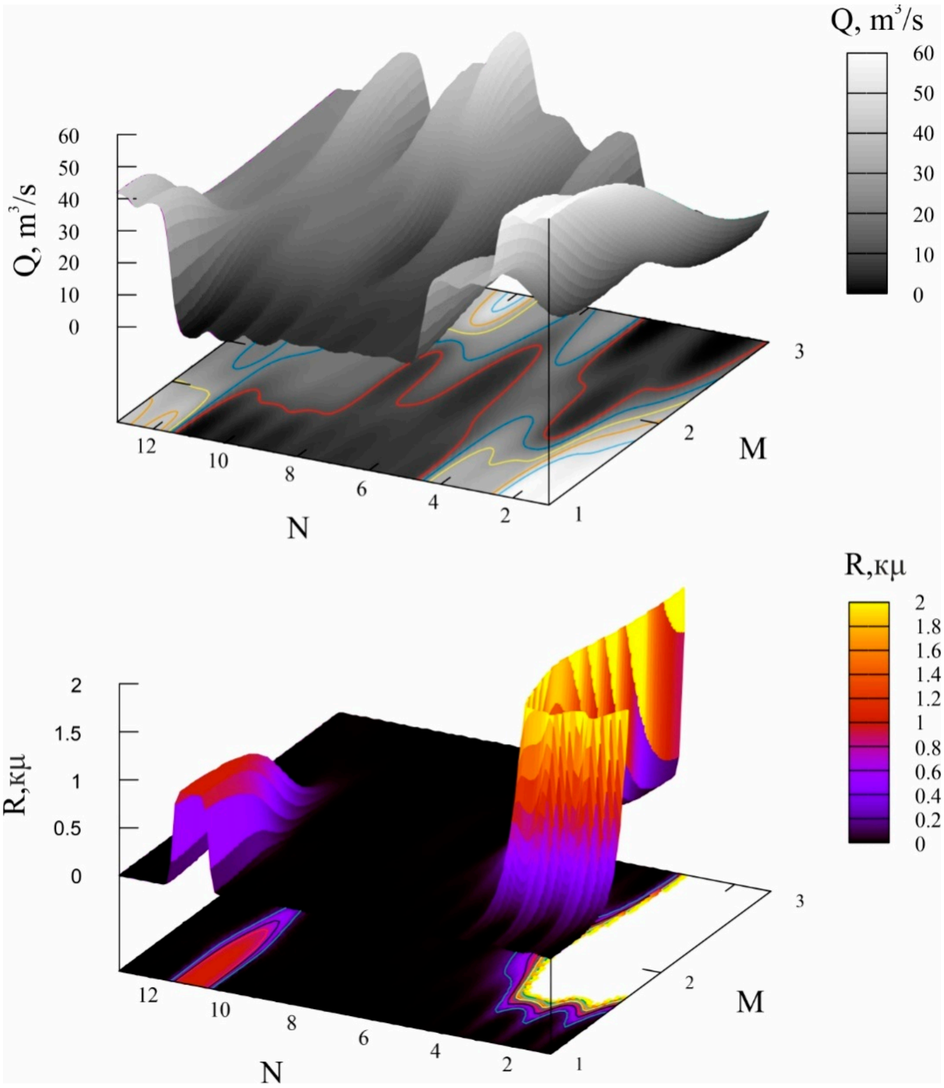

Figure 2. Interrelations of the indicators of the aerologic parameters of the branches (M) in case of the equal length of their sections (N).

The analysis of the projections of the response functions evidences the adequacy of the similarity between the local minima (in most of the studied areas, for example, site N = from 10 to 12) and the fundamental laws of mine ventilation. On the other hand, there are areas on the response surfaces whose interrelations remain difficult to predict. This fact confirms the need to model profile projections of the response, followed by the restoration of the true three-dimensional view of the spherical ventilation network scheme.

4. Conclusions

The authors have obtained a generalized expression for the transfer functions of coalmine facilities, taking into account the delay and a description of the dynamic properties of production units under various modes of functioning. The improved method was used to determine gas dynamic characteristics via additive gas-dynamic processes, using correlation functions of input and output processes. The main results of the work are as follows:

- the stability of gas and explosion safety and air supply of coal mines is significantly affected by diagonal connections, which have their own peculiarities and have different effects on the distribution of air flows and methane emissions in mine workings, influencing fire safety in general. Therefore, building a spherical scheme of the ventilation network using the projections of the response surface will increase the accuracy of identifying diagonal sections to increase the safety of mining operations.
- the most acceptable existing method is that of decomposition, which differs through high accuracy (5–10%), as compared to the previously known ones, by the quality of the search for diagonals of varying complexity and the efficiency of the solution, which is required to control the aerologic safety in coalmines.

The results of the research are recommended for using when designing efficient ventilation schemes of mining areas of coalmines to prevent accidents and the correct placement of sensors to register the methane concentration in airflows. Reducing the fire hazards when developing methane-rich coal beds with high-performance mining faces exclusively through ventilation means is still a difficult task. A complex approach, including advanced technologies for degassing upper beds and mined-out areas, through both surface and underground wells, combined with an increase in the reliability of ventilation control, will significantly improve the situation. Nevertheless, in further studies, it is worth clarifying in more detail the peculiarities of the interrelations of the studied parameters in several projections of the response space.

Author Contributions: Conceptualization and methodology, I.I.B.; validation and formal analysis, R.V.K. and Y.A.T.; investigation, V.V.K. and V.A.K.; resources, I.A.S.; data curation, V.V.K. and V.A.K.; writing—original draft preparation, I.I.B. and N.V.M.; writing—review and editing, N.V.M.; visualization, I.A.S. and Y.A.T.; supervision, R.V.K.; project administration, N.V.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Miao, D.; Lv, Y.; Yu, K.; Liu, L.; Jiang, J. Research on coal mine hidden danger analysis and risk early warning technology based on data mining in China. *Process. Saf. Environ. Prot.* **2023**, *171*, 1–17. [CrossRef]
2. Gu, Z.; Liu, Z.; Wang, Z.; Shen, R.; Qian, J.; Lin, S. Study on characteristics of methane explosion flame and pressure wave propagation to the non-methane area in a connected chamber. *Fire Mater.* **2022**, *46*, 639–650. [CrossRef]
3. De Silva, D.; Gallo, M.; De Falco, L.; Nigro, E. Fire risk assessment of bridges: From state of the art to structural vulnerability mitigation. *J. Civ. Struct. Health Monit.* **2023**, *13*, 351–367. [CrossRef]
4. Chai, J. Investigation of Spontaneous Combustion Zones and Index Gas Prediction System in Goaf of "Isolated Island" Working Face. *Fire* **2022**, *5*, 67. [CrossRef]
5. Wang, H.; Fan, C.; Li, J.; Wu, Y.; Xing, S.; Wang, W. A Field Study of Coal Fire Areas Re-Burning Behavior Assessment and Related Carbon Emissions. *Fire* **2022**, *5*, 186. [CrossRef]
6. Singh, A.K. Subchapter 1.9: Evolution and future prospects for coalbed methane and coal mine methane in India: Approaches for addressing mine safety, climate change, and energy security. In *Innovative Exploration Methods for Minerals, Oil, Gas, and Groundwater for Sustainable Development*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 101–126. [CrossRef]
7. Li, L.; Qin, B.; Liu, J.; Leong, Y.-K. Integrated experimentation and modeling of the formation processes underlying coal combustion-triggered methane explosions in a mined-out area. *Energy* **2020**, *203*, 117855. [CrossRef]
8. Brigida, V.S.; Dmitrak, Y.V.; Gabaraev, O.Z.; Golik, V.I. Use of Destressing Drilling to Ensure Safety of Donbass Gas-bearing Coal Seams Extraction. *Occup. Saf. Ind.* **2019**, *3*, 7–11. [CrossRef]
9. Li, J.; Zhao, Y.; Du, J. Prevention Technology of Coal Spontaneous Combustion Induced by Gas Drainage in Deep Coal Seam Mining. *Fire* **2022**, *5*, 65. [CrossRef]

10. Brigida, V.; Golik, V.I.; Dmitrak, Y.; Gabaraev, O.Z. Ensuring Stability of Undermining Inclined Drainage Holes during Intensive Development of Multiple Gas-Bearing Coal Layers. *J. Min. Inst.* **2019**, *239*, 497–501. [CrossRef]
11. Zhang, F.; Wang, G.; Wang, B. Study and Application of High-Level Directional Extraction Borehole Based on Mining Fracture Evolution Law of Overburden Strata. *Sustainability* **2023**, *15*, 2806. [CrossRef]
12. Hosseini, A.; Najafi, M.; Morshedy, A.H. Determination of suitable distance between methane drainage stations in Tabas mechanized coal mine (Iran) based on theoretical calculations and field investigation. *J. Min. Inst.* **2022**, *258*, 1050–1060. [CrossRef]
13. Jamalan, S.; Sereshki, F.; Ataei, M.; Najafi, M. Numerical modeling of coal gas drainage in a three-dimensional framework. *Arab. J. Geosci.* **2022**, *15*, 826. [CrossRef]
14. Lin, S.; Liu, Z.; Wang, Z.; Qian, J.; Gu, Z. Flame Characteristics in a Coal Dust Explosion Induced by a Methane Explosion in a Horizontal Pipeline. *Combust. Sci. Technol.* **2020**, *194*, 622–635. [CrossRef]
15. Wang, H.; Li, J.; Dong, Z.; Fan, C.; Zhang, Y.; Chen, X. Effect of thermal damage on the pore–fracture system during coal spontaneous combustion. *Fuel* **2023**, *339*, 127439. [CrossRef]
16. Ganova, S.D.; Skopintseva, O.V.; Isaev, O.N. On the issue of studying the composition of hydrocarbon gases of coals and dust to predict their potential hazard. *Bull. Tomsk. Polytech. Univ. Geo Assets Eng.* **2019**, *330*, 109–115. [CrossRef]
17. Cai, Y.; Zhang, Y.; Qi, Q.; Qin, Y.; Zhou, T.; Sun, Z. Optimization of Numerical Simulation Algorithm for Spontaneous Combustion in Goaf via a Compression Storage and Solution Method of Coefficient Matrix. *Fire* **2022**, *5*, 71. [CrossRef]
18. Różański, Z.; Wrona, P.; Pach, G.; Niewiadomski, A.P.; Markowska, M.; Wrana, A.; Frączek, R.; Balcarczyk, L.; Quintana, G.V.; Ruiz, D.d.P. Influence of water erosion on fire hazards in a coal waste dump—A case study. *Sci. Total Environ.* **2022**, *834*, 155350. [CrossRef]
19. Lei, B.; He, B.; Zhao, Z.; Xu, G.; Wu, B. A method for identifying the fire status through ventilation systems using tracer gas for improved rescue effectiveness in roadway drivage of coal mines. *Process. Saf. Environ. Prot.* **2021**, *151*, 151–157. [CrossRef]
20. Roy, D.; Singh, G.; Seo, Y.-C. Coal mine fire effects on carcinogenicity and non-carcinogenicity human health risks. *Environ. Pollut.* **2019**, *254*, 113091. [CrossRef]
21. Kordos, J. Tests of new method of monitoring endogenous fire hazard in hard coal mines. *J. Sustain. Min.* **2019**, *18*, 134–141. [CrossRef]
22. Tarasenko, I.A.; Kulikova, A.A.; Kovaleva, A.M. On the issue of assessing the automation of control of the parameters of the methane-air mixture. *Ugol* **2022**, *11*, 84–88. [CrossRef]
23. Prusek, S.; Krause, E.; Skiba, J. Designing coal panels in the conditions of associated methane and spontaneous fire hazards. *Int. J. Min. Sci. Technol.* **2020**, *30*, 525–531. [CrossRef]
24. Li, F.; Zhang, C.; He, X.; Duan, B.; Wang, C.; Yan, Z. Superposition Risk Assessment and Calculation Model of the Working Position of Coal-Seam Fire Accidents in China. *Fire* **2023**, *6*, 7. [CrossRef]
25. Danish, E.; Onder, M. Application of Fuzzy Logic for Predicting of Mine Fire in Underground Coal Mine. *Saf. Health Work* **2020**, *11*, 322–334. [CrossRef] [PubMed]
26. Muduli, L.; Jana, P.K.; Mishra, D.P. Wireless sensor network based fire monitoring in underground coal mines: A fuzzy logic approach. *Process. Saf. Environ. Prot.* **2018**, *113*, 435–447. [CrossRef]
27. De Silva, D.; Nuzzo, I.; Nigro, E.; Occhiuzzi, A. Intumescent Coatings for Fire Resistance of Steel Structures: Current Approaches for Qualification and Design. *Coatings* **2022**, *12*, 696. [CrossRef]
28. De Silva, D.; Andreini, M.; Bilotta, A.; De Rosa, G.; La Mendola, S.; Nigro, E.; Rios, O. Structural safety assessment of concrete tunnel lining subjected to fire. *Fire Saf. J.* **2022**, *134*, 103697. [CrossRef]
29. Iang, J.; Miao, D. 2021 Research on Coal Mine Risk Control Technology and Platform Base on Big Data. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *647*, 012057. [CrossRef]
30. Luhar, A.K.; Emmerson, K.M.; Reisen, F.; Williamson, G.J.; Cope, M.E. Modelling smoke distribution in the vicinity of a large and prolonged fire from an open-cut coal mine. *Atmos. Environ.* **2020**, *229*, 117471. [CrossRef]
31. Wang, G.-Q.; Shi, G.-Q.; Wang, Y.-M.; Shen, H.-Y. Numerical study on the evolution of methane explosion regions in the process of coal mine fire zone sealing. *Fuel* **2020**, *289*, 119744. [CrossRef]
32. Kim, J.; Lin, S.-Y.; Singh, R.P.; Lan, C.-W.; Yun, H.-W. Underground burning of Jharia coal mine (India) and associated surface deformation using InSAR data. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *103*, 102524. [CrossRef]
33. Bosikov, I.; North Caucasian Institute of Mining and Metallurgy (State Technological University); Klyuev, R.; Khetagurov, V.; Moscow Polytechnic University. Analysis and comprehensive evaluation of gas-dynamic processes in coal mines using the methods of the theory of probability and math statistics analysis. *Sustain. Dev. Mt. Territ.* **2022**, *14*, 461–467. [CrossRef]
34. Shinkevich, M.V.; Kozyreva, E. Specifics of Geomechanical Processes in the Rock Mass when Mining the Coal Seam. *Occup. Saf. Ind.* **2019**, *5*, 33–39. [CrossRef]
35. Kolesnichenko, I.E.; Kolesnichenko, E.A.; Lyubomishchenko, E.I.; Kolesnichenko, E.I. Quantum fundamentals of coal bed methane hazards. *Gornayapromyshlennost* **2021**, *1*, 91–97. [CrossRef]
36. Kudryashov, V.V.; Kobylkin, A.S. Mine air dustiness measurement techniques: Review. *Min. Inf. Anal. Bull.* **2021**, *10-1*, 29–44. [CrossRef]
37. Zhang, C.; Wang, H.; Zhang, X.; Xiao, Y.; Ren, C. The Design and Implementation of AR Glass for Coal Mine Application. *Procedia Comput. Sci.* **2022**, *214*, 1617–1623. [CrossRef]

38. Ray, S.K.; Khan, A.M.; Mohalik, N.K.; Mishra, D.; Mandal, S.; Pandey, J.K. Review of preventive and constructive measures for coal mine explosions: An Indian perspective. *Int. J. Min. Sci. Technol.* **2022**, *32*, 471–485. [CrossRef]
39. Shi, G.-Q.; Wang, G.-Q.; Ding, P.-X.; Wang, Y.-M. Model and simulation analysis of fire development and gas flowing influenced by fire zone sealing in coal mine. *Process. Saf. Environ. Prot.* **2021**, *149*, 631–642. [CrossRef]
40. Balovtsev, S.V. Higher rank aerological risks in coal mines. *Min. Sci. Technol.* **2022**, *7*, 310–319. [CrossRef]
41. Balovtsev, S.V. Comparative assessment of aerological risks at operating coal mines. *MIAB Min. Inf. Anal. Bull.* **2021**, 5–17. [CrossRef]
42. Golik, V.I.; Klyuev, R.V.; Martyushev, N.V.; Brigida, V.; Efremenkov, E.A.; Sorokova, S.N.; Mengxu, Q. Tailings Utilization and Zinc Extraction Based on Mechanochemical Activation. *Materials* **2023**, *16*, 726. [CrossRef] [PubMed]
43. Bosikov, I.; Klyuev, R.; Mayer, A.; Stas, G. Development of a method for analyzing and evaluating the optimal state of aerogasodynamic processes in coal mines. *Sustain. Dev. Mt. Territ.* **2022**, *14*, 97–106. [CrossRef]
44. Puchkov, L.A.; Kaledina, N.O.; Kobylkin, S.S. Systemic approach to reducing methane explosion hazard in coal mines. *Eurasian Min.* **2015**, *2*, 3–6. [CrossRef]
45. Myasnikov, S.V.; Korshunov, G.I.; Kabanov, E.I. The Method of the Comprehensive Assessment and the Forecast of the Occupational Risk of Injury to Coal Mine Personnel during Methane and Dust Explosions. *Occup. Saf. Ind.* **2018**, *10*, 0409–2961. [CrossRef]
46. Yaitskaya, N.A.; Brigida, V.S. Geoinformation technologies in solving three-dimensional geoecological problems. Spatial data interpolation. *Geol. Geophys. Russ. South* **2022**, *12*, 162–173. (In Russian) [CrossRef]
47. Brigida, V.S.; Golik, V.I.; Dzeranov, B.V. Modeling of Coalmine Methane Flows to Estimate the Spacing of Primary Roof Breaks. *Mining* **2022**, *2*, 45. [CrossRef]