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REGULATION AND OPTIMIZATION OF AIR QUANTITY IN A MINE VENTILATION NETWORK WITH MULTIPLE FANS

The ventilation system in underground mine is an important guarantee for workers' safety and environmental conditions. As the mining activities continue, the mine ventilation system is constantly changing. Therefore, to ensure ventilation on demand, the mine ventilation network regulation and optimization are very important. In this paper, the path method based on graph theory is studied. However, the existing path algorithms do not meet the needs of actual mine ventilation regulation and optimization. Therefore, in this paper, the path algorithm is optimized and improved from four aspects. First, based on the depth-first search algorithm, the independent path search algorithm is proposed to solve the problem of false paths in the independent path searched when there is a unidirectional circuit in the ventilation network. Secondly, the independent path calculation formula is amended to ensure that the number of the independent path for the ventilation network with a downcast and an upcast shaft, multi-downcast and multi-upcast shaft and unidirectional circuits is calculated accurately. Thirdly, to avoid both an increase in the number of control points in the multi-fan ventilation network and disturbances in the airflow distribution by determining the reference path through all the independent paths, all the independent paths with the shared fan must be identified. Fourthly, The number and the position of the regulators in the ventilation network are determined and optimized, and the final optimization of air quantity regulation for the ventilation network is realized. The case study shows that this algorithm can effectively and accurately realize the regulation of air quantity of a multi-fan mine ventilation network.

Keywords: mine ventilation network; path method; unidirectional circuit; independent path; regulation and optimization

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1. Introduction

The main tasks of mine ventilation are to ensure the normal breathing of underground workers and the normal operation of aerobic equipment and to dilute and eliminate harmful substances (e.g., underground toxic and harmful gases and ore dust). On this basis, a good underground operation environment is created to ensure the safe, healthy and efficient operation of underground workers. [1]. However, with the continuous development of the underground working face, the structure of the ventilation network and the airflow distribution are constantly changing, causing various problems (e.g., insufficient air quantity, short-circuit of airflow, and circulation of waste air in the part of the air area) that seriously affect the underground ventilation quality, ventilation efficiency and distribution of airflow, which in turn directly threaten the safety of the underground work [2-5].

Mine ventilation network regulation and optimization is an effective method for solving such problems as a lack of air, short-circuiting of airflow and an unreasonable air quantity distribution. At present, there are two major research approaches for mine ventilation network regulation and optimization [6-7]: one approach involves graph theory-based methods [8-10]; and the other approach involves mathematical programming methods [11-14]. Graph theory is used by major mine ventilation commercial software, such as Ventsim, VnetPC, VentGraph, VUMA-network, and iVent [15-20]. The two types of methods have their own advantages and disadvantages, but their goals are the same, that is, to meet the air area requirements and minimize energy consumption [21]. In this paper, we focus on graph theory-based methods for ventilation network regulation and optimization. Its theoretical basis can be traced back to the early 1950s, which Scott D.R. and Hinsley F.B. improved the Cross method of pipeline water network calculation, and successfully used computer technology to calculate the air quantity distribution of mine ventilation network [22]. On the basis of the Scott-Hinsley algorithm, in order to adapt to more complex mine ventilation network calculations and meet the needs of air quantity distribution on demand, domestic and foreign researchers have conducted a lot of research. One of them is the research on the optimization of air quantity regulation based on graph theory. For example, Trutwin [23] used Gauss-Seidel iterative method to solve the problems of non-steady-state and automatic control in mine ventilation network. Wang [24] proposed a method to find the maximum resistance route as the key path to adjust the air quantity distribution of mine ventilation network. Xu et al. [25] used a method, that is, by searching all the independent paths of the whole ventilation network, determining the reference path, calculating the pressure difference between each independent path and the reference path, so as to realize the on-demand regulation of the whole ventilation network. Hu et al. [26] proposed the longest path algorithm to determine the location and parameters of regulators, and used other methods (such as the cut-set method) to transfer the location of regulators. Wang et al. [27] proposed a fixed air quantity method which can directly adjust the fixed air quantity branch to meet the requirement for air quantity. Chen et al. [2] put forward a method that combined improved differential evolution algorithm with CPM, namely IDECP method, to realize the optimization of air quantity regulation. It can be seen that the mine ventilation network regulation methods graph theory-based mainly include the fixed air quantity method, loop method, and path method [27]. There are two major drawbacks of the fixed air quantity method: it can only regulate the fixed air quantity branch and may increase the total pressure drop of the mine, resulting in increased ventilation energy consumption [28-29]. In the loop method, which involves regulating the local loop of the ventilation network to meet the air quantity requirements, the branch with the increased pressure drop may be the branch on the maximum resistance route, which would cause an increase in the total energy consumption of the mine [30-31]. The path method can solve not only the limitation of the regulation position and range in the fixed air quantity method but also the problem that the fixed air quantity method and the loop method are likely to increase the total energy consumption of the mine [32].

The path method has the above advantages and is studied by scholars engaged in mine ventilation. The path matrix algorithm and search algorithm, the depth-first search algorithm, a greedy algorithm, and an interactive path regulation method of minimum power consumption et al. were used to search the independent path and determine both the number and position of the regulator [33-38]. Despite the important accomplishments of prior research studies, several issues remain: (1) when the ventilation network contains one or more unidirectional circuits, the independent path searched may contain false paths; (2) the searching of all paths does not guarantee that the paths are independent of each other; (3) the position of the regulators does not consider the actual situation of the mine, and the number of the regulators is not optimized, resulting in difficulty in ventilation management and excessive energy consumption; and (4) for the regulation of a multi-fan ventilation network, the reference path is usually determined by all independent paths of the ventilation network, causing an increase in the number of regulators of the entire ventilation network and the other branches that have met the requirements of the air quantity before the regulation cannot be satisfied.

Therefore, in this paper, a regulation and optimization algorithm for a mine ventilation network with multiple fans is proposed based on the existing path method. The algorithm consists of the independent path search algorithm (IPSA), a correction formula used to calculate the number of independent paths, a method for determining its reference path with all independent paths containing the same fan, and the public branch method, used to determine and optimize the positions and number of regulators. The public branch method is based on the completion of the independent path search and the determination of the reference path, eliminating the branches on the reference path and the nonadjustable branches of the ventilation network, and calculating the number of branch paths of the remaining branches (i.e., the number of branches occurring in all paths). Moreover, the number of branch paths of all branches is sorted from high to low. In addition, the regulation process follows the principle that branches with a large number of branch paths are regulated first, and the branches that can regulate the largest number of the paths and have the smallest regulation values are preferentially selected. The optimization refers to the optimization of the position and number of regulators to reduce the number of regulators and avoid the increase of energy consumption under the premise of meeting the air quantity requirements of each air demand area. The example tests show that the algorithm can effectively avoid the unidirectional circuit in the ventilation network, accurately calculate the number of independent paths, exactly determine all the independent paths to be regulated and their reference path, and determine and optimize the positions and number of regulators. Finally, the air quantity requirements of all air demand areas in the ventilation network are met.

2. Methodology

Before introducing the principle of the path method, several important terminology need to be explained. (1) The path refers to the route of all branches along the airflow direction for any ventilation network from the air intake branch to the air return branch. (2) the independent path means that for each independent path defined, at least one branch of the path has not been used by other paths until all the branches have been used. Therefore, all independent paths can express all other non-independent paths in the ventilation network. (3) The maximum resistance route is the path where the sum of the resistance value of all branches of an independent path is the largest. (4) The total resistance value of an independent path is selected as the reference value of the regulation, and the independent path is the reference path.

In mine ventilation, the path method refers to the following steps: first, the calculation of the sum of the pressure drop for each independent path on the basis of searching all the independent paths from the inlet node of the inlet branch to the outlet node of the outlet branch in the entire ventilation network and then selecting one reference path from all the independent paths; next, the determination of pressure drop of the regulators and means of ventilation regulation by the pressure difference between the reference path and the independent path; and finally, the successful regulation of the entire ventilation network through the installation of regulators.

The path [27,39] is represented by a matrix $P = (p_{ij})_{t \times n}$ (t means the number of all paths, n is the number of branches), where

$$P_{ij} = \begin{cases} 1, & j \text{ branch in path } p_i \\ 0, & j \text{ branch is not in path } p_i \end{cases}$$

Assume that $H^T = [h_1, h_2, ..., h_n]$, where $h_i = R_i Q_i^2$, H is the column vector of pressure drop of each branch in the ventilation network; h_i is the pressure drop of the i-th branch, Pa; R_i is the resistance value of the i-th branch, $N \cdot s^2 \cdot m^{-8}$; Q_i is the air quantity value of the i-th branch, m^3/s. thus, the following is valid:

$$H_P = P \cdot H \tag{1}$$

In formula (1), H_P is the total pressure drop column vector for each independent path, $H_P^T = [h_1, h_2, ..., h_t]$; P is the path matrix; H is the pressure drop column vector for each branch in the ventilation network.

A path is selected as a reference path in all the independent paths, and the entire ventilation network is controlled with the reference path as the goal. If the selected reference path has the maximum pressure drop, then the regulation of the entire ventilation network can only be regulated by increasing pressure value. At this point, the path method is also called the "maximum resistance route method". Assuming that the pressure drop of the reference path is h_0, the pressure difference for other non-reference paths are

$$\Delta h_i = h_i - h_0 \tag{2}$$

Where h_i is the pressure drop of the i-th path; Δh_i is the pressure difference between the i-th path and the reference path, i.e., the pressure drop of the regulator on the i-th path, Pa.

Therefore, the pressure difference value for each non-reference path is calculated, and a path regulation vector $\Delta H_P^T = (\Delta h_1, \Delta h_2, ..., \Delta h_t)$ can be obtained. Where

- If $\Delta h_i > 0$, then the pressure difference must be decreased to regulate the ventilation network. Here, Δh_i is the pressure difference value to be lowered.
- If $\Delta h_i < 0$, then the pressure difference must be increased to regulate the ventilation network. At this time, the regulator must be installed, and the corresponding $|\Delta h_i|$ is the pressure drop of the regulator.

Therefore, the specific steps of the path method can be summarized as follows:

- First, before the ventilation network is regulated, the ventilation network is constructed correctly, the fixed air volume is set and the ventilation network is correctly solved.
- Second, the independent paths are correctly searched, and the pressure drop of each independent path is calculated.
- Third, the reference path is determined.
- Fourth, based on the correct calculation of the regulated pressure drop, the number and the locations of the regulators are determined and optimized.

Finally, on-demand ventilation of the entire ventilation network is completed.

3. Problem analysis

From the point of view of overall regulation, because the path method regulates all the independent paths from the inlet node of the inlet branch to the outlet node of the outlet branch in the entire ventilation network, the regulation position and range are relatively flexible. As a result, the path method can avoid increasing the pressure value to regulate the path of the maximum resistance route, which leads to increased energy consumption; thus, the path method is relatively superior to the fixed quantity method and loop method. However, four major issues must be solved in this method. First, when there is a unidirectional circuit in the ventilation network, the independent path search is prone to false path problems. Secondly, a method is required to determine how to accurately calculate the number of independent paths in the ventilation network. Thirdly, accurate determination of the reference path of the multi-fan ventilation network is required. Fourthly, a method to determine and optimize the locations and number of regulators is required. The above four problems are analyzed in detail in Sections 3.1-3.4.

3.1. The unidirectional circuit

When there is a unidirectional circuit in the ventilation network, there is recirculating airflow in the ventilation network; such recirculating airflow is generally generated by a fan or natural ventilating pressure in the mine ventilation system or a manually controlled circulation of airflow [40]. Circulating airflow is prone to occur in underground mines using a multi-fan and multi-stage fan station or an unreasonable fan installation. Therefore, the unidirectional circuit is a problem that must be addressed using an independent path searching method in a mine ventilation network.

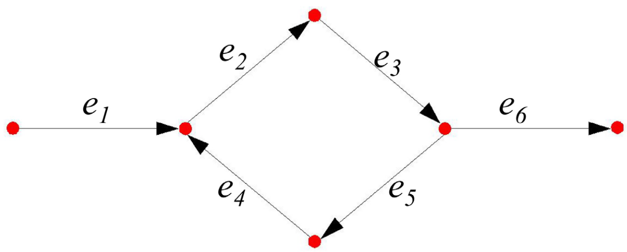


Fig. 1. Ventilation network with a unidirectional circuit

In Fig. 1, when the independent path of the ventilation network is searched using the depth-first search algorithm, the paths P_1 ($e_1 \rightarrow e_2 \rightarrow e_3 \rightarrow e_6$) and P_2 ($e_1 \rightarrow e_2 \rightarrow e_3 \rightarrow e_5 \rightarrow e_4 \rightarrow e_2 \rightarrow e_3 \rightarrow e_6$) are searched. However, P_2 is a false path, and thus, the ventilation network cannot be accurately regulated.

To solve the problem that the independent path search may identify false paths, the independent path search algorithm (IPSA) is proposed based on an in-depth study of existing independent path search methods. The IPSA is based on the depth-first-search method; in the process of searching independent paths, the IPSA can automatically determine whether there is the unidirectional circuit in the ventilation network and guarantee that the number of independent paths is accurate. The IPSA saves the current search path by using the stack that has the characteristics of "first-in-last-out, last-in-first-out" and uses such operations as pushing the stack and popping the stack to complete an accurate search of independent paths, ultimately ensuring that all independent paths are accurately searched. The algorithm is described in detail in Section 4.

3.2. The number of independent paths

To ensure the accuracy of regulation by the path method, all paths searched in the ventilation network must be independent; the accuracy is restricted by the number of independent paths. Otherwise, all the paths in the ventilation network will be searched instead of independent pathways, thereby increasing the difficulty of regulation and causing control repetition, eventually leading to incorrect control results. In general, the number of independent paths in the ventilation network is equal to the number of basic circuits in the ventilation network [1,27]. That is,

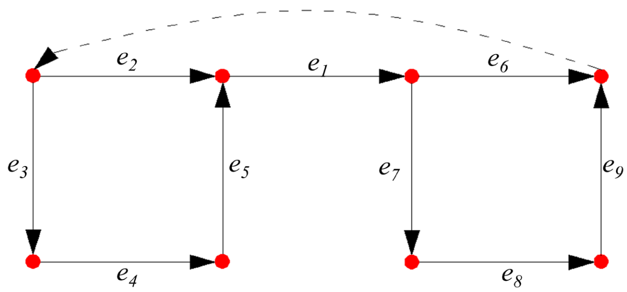
$$M = N - J + 1 \tag{3}$$

where M is the number of independent paths, N is the number of branches, and J is the number of nodes (similarly hereinafter).

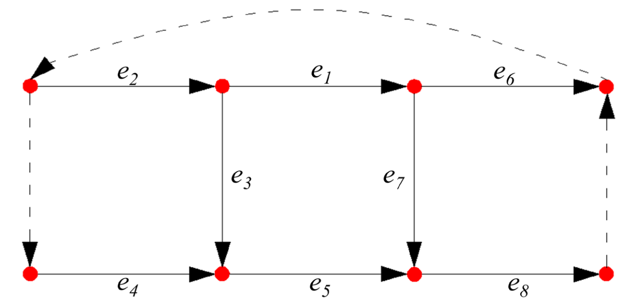
3.2.1. Ventilation network with a downcast and an upcast shaft and the multi-downcast and multi-upcast shaft

Fig. 2(a) is a downcast and an upcast shaft ventilation network, that is, the ventilation network with only one intake branch and one return branch. Fig. 2(b) is a ventilation network with multi-downcast and multi-upcast shaft, where the dashed line represents the virtual branch, that is, the ventilation network with two or more intake branches and return branches. The path of the ventilation network in Fig. 2(a) contains P_1 ($e_2 \rightarrow e_1 \rightarrow e_6$), P_2 ($e_2 \rightarrow e_1 \rightarrow e_7 \rightarrow e_8 \rightarrow e_9$), P_3 ($e_3 \rightarrow e_4 \rightarrow e_5 \rightarrow e_1 \rightarrow e_6$), and P_4 ($e_3 \rightarrow e_4 \rightarrow e_5 \rightarrow e_1 \rightarrow e_7 \rightarrow e_8 \rightarrow e_9$). The path matrix composed of P_1, P_2, P_3, and P_4 has a rank of 3; that is, the number of independent paths in Fig. 2(a) is 3. Similarly, the rank of the path matrix of the ventilation network in Fig. 2(b) is 4, i.e., the number of independent paths is 4. According to the independent path number formula (3), the number of independent paths in Fig. 2(a) is 2, and the actual number of independent paths is 3; the number of independent paths in Fig. 2(b) is 1, and the actual number of independent paths is 4. There is a difference between the calculation result of the calculation formula (3) for the independent path number and the calculation result of the path matrix.

However, whether a mine ventilation system with a downcast and an upcast shaft or a mine ventilation system with multi-downcast and multi-upcast shaft is being considered, the branches



(a) The ventilation network with a downcast and an upcast shaft



(b) The ventilation network with multi-downcast and multi-upcast shaft

Fig. 2. Ventilation networks

which include the downcast shaft and the upcast shaft in the system are connected to each other through the atmosphere. Therefore, the atmosphere can be viewed as one or more wind-free atmospheric branches and nodes for which its resistance is zero (also called virtual branches and virtual nodes) connected to the mine ventilation network to ensure its connectivity. After ventilation network with a downcast and an upcast shaft and a ventilation network with multi-downcast and multi-upcast shaft are added to the virtual branch or virtual node, the number of independent paths in Figs. 2(a) and (b) is 3 and 4, respectively, according to formula (3), in accordance with the calculation of the path matrix. Therefore, the number of branches N and the number of nodes J in formula (3) should include the number of virtual branches and the number of virtual nodes.

$$M_c = N + N_v - J - J_v + 1 \tag{4}$$

where M_c is the number of independent paths after correction, N_v is the number of virtual branches and J_v is the number of virtual nodes (similarly hereinafter).

3.2.2. Ventilation network with unidirectional circuit

In Fig. 1, two independent paths P_1 and P_2 are searched, but P_2 is a false path and cannot participate in regulation. Therefore, the actual number of independent paths in Fig. 1 is one. However, according to the independent path number correction formula (4), the number of independent paths in Fig. 1 is 2, which contains a false path P_2. Therefore, for a ventilation network with unidirectional circuits, the number of unidirectional circuits should be subtracted from the number of independent paths in the ventilation network. The corrected formula for calculating the number of independent paths is

$$M_c = N + N_v - J - J_v - C_l + 1 \tag{5}$$

where C_l is the number of unidirectional circuits in the ventilation network (similarly hereinafter). It should be noted that formulas (4) and (5) serve the IPSA algorithm proposed in this paper to ensure that the number of independent paths in the mine ventilation network can be correctly searched.

3.3. Determination of the reference path

On the basis of the balance of air quantity, to balance the air pressure of the entire ventilation network, a reference path should be selected as the target of regulation. The total pressure drop of the other non-reference paths in the ventilation network is equal to the total pressure drop of the reference path through reducing the pressure drop, increasing the air pressure value, and increasing the pressure drop to realize ventilation on demand. This method is undoubtedly correct for the ventilation network with a single fan. However, for ventilation networks with multiple fans, the independent path with a fan is different, and its total pressure drop is different; thus, the air pressure of each fan is different. Therefore, the multi-fan ventilation network generally selects a reference path and then regulates the total pressure drop of other non-reference paths to be equal to the total resistance of the reference path; as a result, the air quantity of the entire ventilation network is redistributed, and the number of regulators will significantly increase. This approach does not meet the regulation requirements.

In fact, the absolute value of the total resistance on an independent path is equal to the absolute value of the sum of the negative pressures of the fans on the independent path, i.e., the total pressure drop of independent paths sharing the same fan (when there are other fans on the independent path, the negative pressure of the fan must be added) is equal to the absolute value of the negative pressure of the fan. Therefore, when the branch with fixed air quantity(Generally, the air quantity value of a branch is fixed to its required air quantity value, that is, the branch is called the branch with fixed air quantity.) is only used on an independent path shared by one fan, only the independent paths sharing the fan are regulated; this approach can meet the regulation requirements and does not affect other ventilation areas that have met the air quantity requirement. The determination of the reference path for the ventilation network with multiple fans is not determined on the basis of all the independent paths of the entire ventilation network but instead based on the fan in the independent path that is the fixed air quantity branch and all independent paths that share the same fan.

3.4. Determine and optimize the number and position of regulators

To regulate the entire ventilation network, the number of regulators and the locations of the regulators of the entire ventilation network must be determined [31]. However, in an actual mine, the actual situation of the roadway should be considered when the positions of the regulators are set. For example, increased resistance regulation is typically adopted in the air demand area, and the air inlet and outlet area, series air paths, high-resistance air routes, and main transportation routes are generally regulated by lowering resistance. Moreover, during the regulation of the ventilation network, the position of the regulators should be determined such that its influence on other branches of the ventilation network that meet the air volume requirement is minimized to avoid an increase in the number of regulators, which in turn causes other branches do not meet the air quantity requirements. In addition, from the perspective of mine ventilation management, the number of regulators should be as small as possible to minimize the difficulty of ventilation management.

Given the restriction on the location of the regulators based on the objective conditions of the mine and the increased difficulty of mine management caused by an increased number of regulators, the public branch method is adopted to determine and optimize the number of regulators and the locations of the regulators. The public branch method is based on the completion of the independent path search and the determination of the reference path, eliminating the branches on the reference path and the nonadjustable branches of the ventilation network, and calculating the number of branch paths of the remaining branches (i.e., the number of branches occurring in all paths). Moreover, the number of branch paths of all branches is sorted from high to low. In addition, the regulation process follows the principle that branches with a large number of branch paths are regulated first, and the branches that can regulate the largest number of the paths and have the smallest regulation values are preferentially selected. Finally, the number of regulators and the positions of the regulators are determined and optimized to achieve regulation of the entire ventilation network [6].

4. Regulation and optimization algorithm

The path regulation and optimization algorithm is based on the assumption that the airflow is incompressible in the roadway and that the airflow is a completely turbulent and steady flow. The IPSA is used to complete the correct search of the independent path, and the total pressure drop of all independent paths are calculated. Furthermore, a method based on the shared fan to determine the regulated independent paths and the reference path is proposed. In addition, the number of regulators and the positions of the regulators are determined by the public branch method to regulate the entire ventilation network.

Several concepts related to path regulation and optimization algorithms are defined below:

(1) Current search node: the top element of the stack, which is the current node in the depth-first search traversal.

(2) Node access status: to mark the status of the search node, it is divided into three statuses: not accessed, to be accessed and accessed; all nodes are not accessed when they are initialized, and the nodes in the stack, except the top element of the stack, are all accessed.

(3) Branch access status: to mark the status of the search branch, it is divided into two statuses: not accessed and accessed; all branches are not accessed when the branch is initialized, and branches on the current search path are already accessed.

A flowchart of this algorithm is shown in Fig. 3, and the specific steps are as follows:

Step 1: Initialize the ventilation network parameters: *N* branches, N_v virtual branches, *J* nodes, J_v virtual nodes, C_l loops, *M* paths, and all nodes and branches are set to the not-accessed status. The number of paths *M* satisfies the formula (5).

Step 2: Build the topology relationships of the ventilation network.

Step 3: Search for the air inlet branch of the mine ventilation network using the beginning node of the air inlet branch as the starting point for an independent path search.

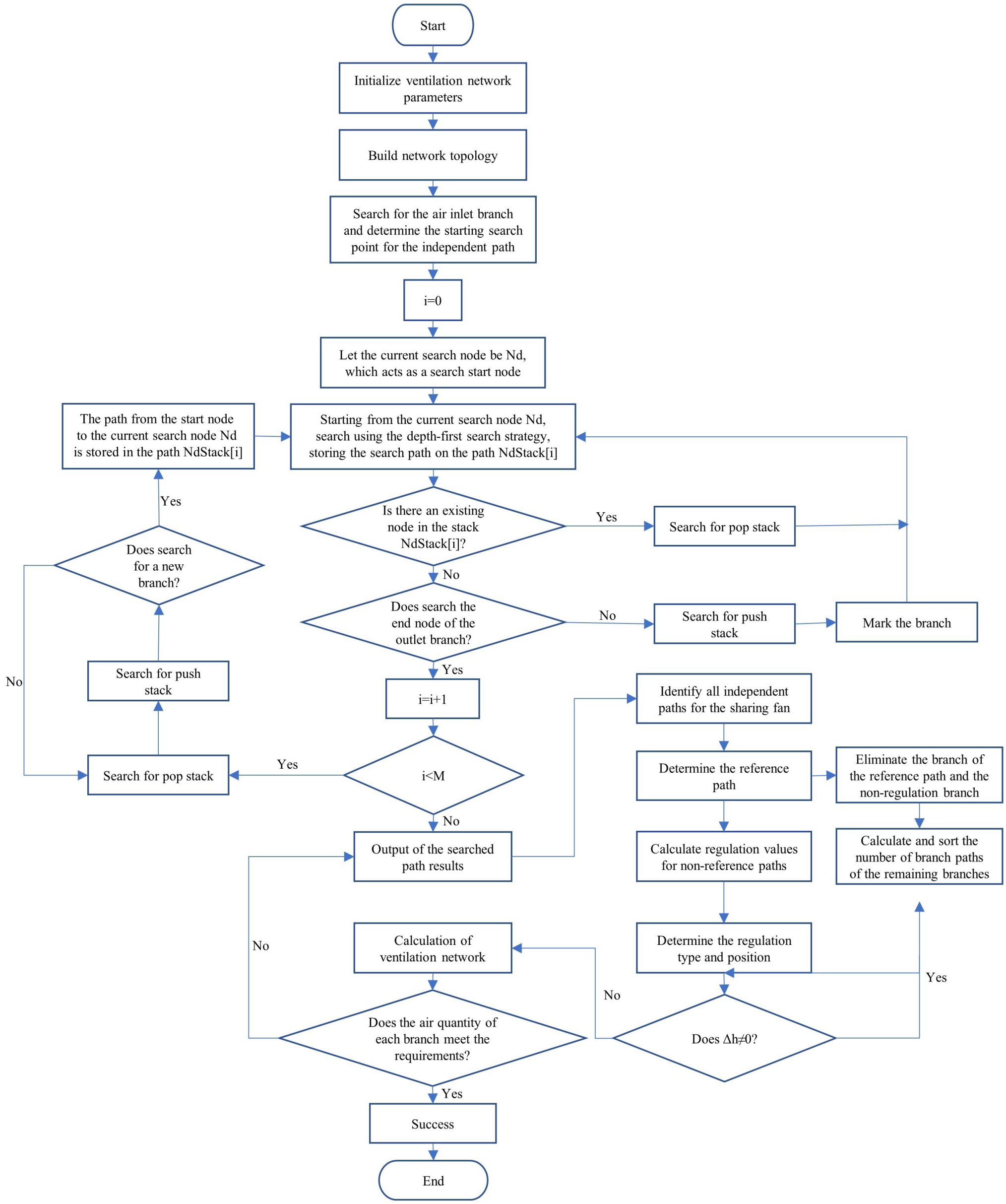


Fig. 3. The flow diagram of regulation and optimization algorithm

Step 4: Initialize the stack NdStack; starting from the current search node Nd, the search starting point is set to the status of to be accessed. The path is searched for a depth-first search strategy and stored in the stack NdStack [*i*]. The stack Ndstack [*i*] is used to store all nodes of the *i*-th independent path.

Step 5: Determine whether the current node is accessed in the stack NdStack [*i*]. If not, then enter step 6; if so, then stop the search, and pop the stack to search for the starting node of the stack.

Step 6: Determine whether the end node of the outlet branch is searched. If so, then *i* in stack NdStack [*i*] becomes $i + 1$; if not, then continue to push the stack and mark the branch.

Step 7: Determine whether i in stack NdStack [*i*] is less than the total number of independent paths M. If $i < M$, then a pop-stack search is performed, and step 8 is initiated. If $i \geq M$, then the result of searching for all independent paths is output, and Step 9 is initiated.

Step 8: The pop-stack search starts from the top of the stack, goes to the next node and continues to determine whether a new branch is found. If a new branch is not found, then the pop stack search is continued; if a new branch is found, the results from the starting point to the current search node Nd of the path are stored in stack Ndstack [*i*], then Step 4 is initiated.

Step 9: According to the fixed air quantity branch, all the independent paths sharing the same fan are determined, and the total pressure drop of each independent path is calculated.

Step 10: Determine the reference path according to the actual regulation requirement of the ventilation network.

Step 11: Calculate the regulation value of each non-reference path, remove the reference path branch and nonregulatable branch, count the number of branch paths of the remaining branches, and then sort them from high to low.

Step 12: Regulate the ventilation network according to the number of branch paths from high to low, preferentially select the branch with the highest number of regulatable paths and the smallest regulation value, and then determine the regulation means and optimize the position of the regulation point.

Step 13: Determine whether there is an independent path of $\Delta h \neq 0$ in the ventilation network. If so, then skip to Step 12; if not, then proceed to Step 14.

Step 14: The ventilation network is solved to determine whether the air quantity of each branch satisfies the requirement. If not, then skip to step 9; if so, then the optimization and regulation of the ventilation network are successful, and the program ends.

5. A case study and results

For a better understanding of the algorithm, an example of a simple network is given. In addition, the network must satisfy the conditions that the airflow is incompressible in the roadway and that the airflow is a completely turbulent and steady flow. Fig. 4 shows a ventilation network with multiple fans, which is from the literature Chen K. et al. [2]; the network includes 3 fans, 15 nodes, 20 branches, 1 virtual branch, 0 virtual nodes, and 0 unidirectional circuits. The original branch ventilation parameters are shown in Table 1. e_{17}, e_{18}, and e_{19} are preselected fan branches with air quantity of 24, 52, and 25 m^3/s, respectively, e_{12} is the fixed air quantity branch, and the fixed air quantity is $Q_{12} = 1.5$ m^3/s. The airflow direction before and after the regulation of branch e_{12} is shown in Fig. 4, and the direction of the airflow after the regulation is v_8 to v_{11}. Finally, the result of the forced ventilation airflow distribution is shown in Table 1.

In Table 1, *R* represents resistance; *Q* represents air quantity; Δh represents the regulation value; NR represents a non-regulatable branch, and IR indicates that the branch can be regulated by increasing the pressure drop.

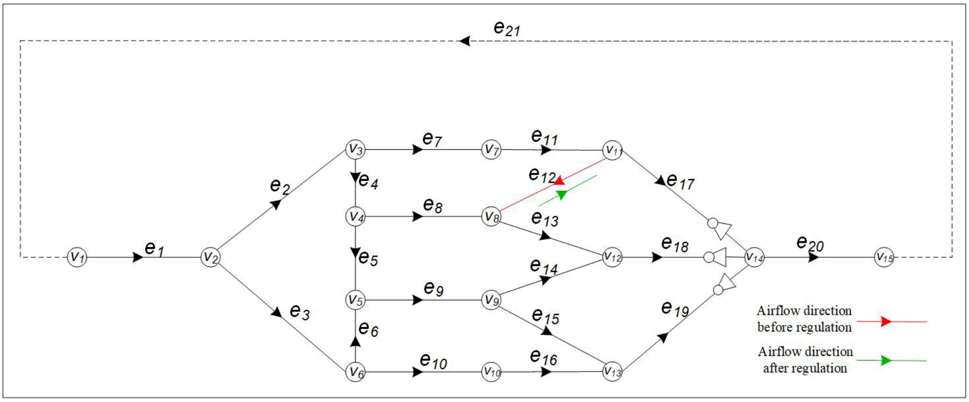


Fig. 4. Multi-fan ventilation network

TABLE 1

Multi-fan ventilation network parameters and regulation results

Branch Index	**Initial parameters**		**Forced ventilation**	**Ventilation on demand**		**Branch type**	**Regulation type**
	R/N·s²·m⁻⁸	***Q*/m³·s⁻¹**	***Q*/m³·s⁻¹**	***Q*/m³·s⁻¹**	**Δ*h*/Pa**		
1	0.01	101.00	101.00	101.00	0	Inlet	NR
2	0.08	55.74	54.37	54.37	0	General	IR
3	0.14	45.26	46.63	46.63	0	General	IR
4	0.20	29.01	31.87	31.86	0	General	IR
5	0.65	2.46	2.96	2.96	0	General	IR
6	0.20	25.89	26.53	26.53	0	General	IR
7	1.20	26.73	22.50	22.50	421.59	General	IR
8	1.00	26.55	28.90	28.90	0	General	IR
9	1.00	28.36	29.49	29.49	0	General	IR
10	1.20	19.37	20.10	20.10	0	General	IR
11	0.02	26.73	22.50	22.50	0	General	IR
12	0.30	2.73	–1.50	–1.50	0	Fixed-airflow	IR
13	0.32	29.28	27.40	27.41	0	General	IR
14	0.33	22.72	24.60	24.59	0	General	IR
15	0.01	5.63	4.90	4.90	0	General	IR
16	1.30	19.37	20.10	20.10	0	General	IR
17	0.12	24.00	24.00	24.00	–1,548.70	Fixed fan	NR
18	0.08	52.00	52.00	52.00	–1,935.60	Fixed fan	NR
19	0.21	25.00	25.00	25.00	–1,650.48	Fixed fan	NR
20	0.01	101.00	101.00	101.00	0	Outlet	NR
21	0	101.00	101.00	101.00	0	Virtual	NR

Note: Forced ventilation refers to that some branches are set as fixed air quantity in the ventilation network, and the air quantity of these branches is forced to reach the fixed air quantity value, resulting in an unbalanced pressure drop in the loop where the fixed air quantity branch is located. The unbalanced pressure drop is the basis of air quantity regulation and optimization.

According to the result of the forced ventilation airflow distribution and formula (5), 7 independent paths in the ventilation network are searched, as shown in Table 2. The path where the fixed air quantity branch e_{12} is located is P_2, and the fan branch on P_2 is e_{17}. Therefore, the independent paths that share the e_{17} fan branch are P_1 and P_2; thus, only these two paths must be regulated. In addition, because the regulatable branches of P_1 and P_2 are all increased resistance regulation, the maximum resistance path P_2 is chosen as the reference path. Thus, after eliminating the branch of the reference path and the nonregulatable branch, the regulatable branches are e_7 and e_{11}. In addition, the number of branch paths of e_7 and e_{11} is calculated as 1; thus, one of e_7 and e_{11} is selected randomly. Therefore, e_7 is selected in this example, and its regulatable value is 421.59 Pa; the negative pressures of the three fans are 1,548.70, 1,935.60, and 1,650.48 Pa. Table 1 shows the airflow distribution after regulation and optimization.

TABLE 2

All independent paths and its total pressure drop for ventilation network in Fig. 4

Path	Branch and airflow direction	Total pressure drop/ Pa
P_1	$e_1 \rightarrow e_2 \rightarrow e_7 \rightarrow e_{11} \rightarrow e_{17} \rightarrow e_{20}$	1,043.23
P_2	$e_1 \rightarrow e_2 \rightarrow e_4 \rightarrow e_8 \rightarrow e_{12} \rightarrow e_{17} \rightarrow e_{20}$	1,607.45
P_3	$e_1 \rightarrow e_2 \rightarrow e_4 \rightarrow e_8 \rightarrow e_{13} \rightarrow e_{18} \rightarrow e_{20}$	1,980.50
P_4	$e_1 \rightarrow e_2 \rightarrow e_4 \rightarrow e_5 \rightarrow e_9 \rightarrow e_{14} \rightarrow e_{18} \rightarrow e_{20}$	1,979.85
P_5	$e_1 \rightarrow e_2 \rightarrow e_4 \rightarrow e_5 \rightarrow e_9 \rightarrow e_{15} \rightarrow e_{19} \rightarrow e_{20}$	1,684.18
P_6	$e_1 \rightarrow e_3 \rightarrow e_6 \rightarrow e_9 \rightarrow e_{15} \rightarrow e_{19} \rightarrow e_{20}$	1,684.18
P_7	$e_1 \rightarrow e_3 \rightarrow e_{10} \rightarrow e_{16} \rightarrow e_{19} \rightarrow e_{20}$	1,683.77

6. Conclusions

In this paper, to realize the regulation and optimization of air quantity in a mine ventilation network with multiple fans, the IPSA algorithm is proposed based on previous research. First, the algorithm can automatically judge and effectively evaluate whether there are unidirectional circuits in the ventilation network, thereby effectively avoiding the existence of false paths in the independent paths searched. Secondly, in the mine ventilation network with single-inlet-single-outlet, multiple-inlet-multiple-outlet, and unidirectional circuits, it can ensure the accurate calculation of the number of independent paths. Thirdly, by using the shared fan to determine the independent paths and its reference path, the algorithm can reduce the number of regulators and the difficulty of regulation, especially for complex ventilation networks with multiple fans and a large number of branches. Finally, it can optimize the location and number of regulators, further reduce the number of regulators and the difficulty of ventilation management, to realize air quantity to meet the requirements of mine ventilation demand and reduce ventilation energy consumption.

The case study showed that this optimization algorithm is suitable for not only mine ventilation networks with a downcast and an upcast shaft, or multi-downcast and multi-upcast shaft, but also a multi-fan mine ventilation network; moreover, the algorithm can provide a more economical and reasonable air quantity regulation optimization scheme for actual mine ventilation systems and has a certain guiding significance for mine ventilation performance. Finally, considering the complexity of the ventilation network and the increase in the number of fans, the algorithm may need further verification and research.

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