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Research on the Calculation of Mine Ventilation Network Based on Loop Airflow Method

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Abstract: In response to the need to further explore the potential of existing mine ventilation network solutions, a mine ventilation network solution was carried out based on the loop air volume method. A computer program design framework for loop method ventilation network solution was constructed, and ventilation network solution software was developed. Combined with the ventilation data of Yuyang Coal Mine, the application solution was carried out. The research results indicate that the accuracy of the mine air volume obtained through this calculation method and the developed software is relatively high, with a total air volume error of less than 0.5. This has important theoretical and practical significance for overall control of the mine ventilation status and decision-making.

Keywords: Mine ventilation; ventilation network; loop air volume method; solution; error.

1. Introduction

The mine ventilation system is a critical component in ensuring safe mining operations, where the accuracy and efficiency of network resolution directly impact the reliability of ventilation control and the effectiveness of hazard prevention [1-3]. With increasing mining depths and system complexity, traditional ventilation network solution methods (such as the air volume balance method and node pressure method) have shown limitations in handling high-dimensional nonlinear systems. The loop air volume method, as a mathematical modeling approach based on pressure balance equations, significantly improves the computational efficiency and stability of complex networks by transforming ventilation network topology into independent loop equation systems [4-5]. In recent years, domestic and international scholars have conducted extensive research on the theoretical refinement, algorithmic optimization, and engineering applications of the loop air volume method. Zhong Deyun et al. [6] systematically investigated the computational principles of the loop air volume method and proposed an improved Scott-Hinsley algorithm. Tian Ziwen et al. [7] developed a rapid computational algorithm for complex ventilation networks and applied it to the iterative solution module of the "Huangfang Coal Mine Ventilation Intelligent Decision System." The results demonstrated that the air volume calculation errors were all below 5%, meeting engineering requirements. Wang Pengfei et al. [8] conducted full-scale mine ventilation network calculations based on the loop air volume method. By designing preprocessing steps for the ventilation network model and exploring different application scenarios, combined with ventilation data from the Bofang Coal Mine, they achieved a solution accuracy of over 90%, a convergence time of less than 10 seconds for networks with up to 1,000 branches, and loop resistance adjustment errors below 0.5%. However, the potential of this method in dynamic network regulation, multi-objective optimization, and intelligent computation still requires further exploration. Therefore, building upon existing research, this paper conducts a systematic analysis of the key technologies in the loop air volume method, aiming to provide theoretical support for the precise regulation of mine ventilation systems.

2. Theory of Loop Airflow Method

2.1. Basic principle of ventilation

When the wind flows in the wind network, it follows the laws of conservation of mass and energy, namely Kirchhoff's law. These laws are applicable to any form of wind network, regardless of whether the air volume is distributed according to demand or naturally, and therefore serve as the theoretical basis for calculating ventilation networks. The loop air flow method is actually based on graph theory and the basic laws of air flow. It uses the Gauss Seidel iteration method to sequentially solve the corrected air flow of the mesh until a predetermined accuracy is reached, in order to obtain asymptotic quantities that approach the true solution of the system of equations. The law of air volume balance and the law of air pressure balance constitute an N-order nonlinear large-scale equation system with air volume as the unknown variable. It is very difficult to directly solve such a system of equations, and it is generally solved through linearization of nonlinear equations.

If the wind pressure balance equation is expanded according to Taylor's formula and high-order terms are omitted, the K-th linear approximation calculation formula is:

$$\begin{aligned} f_i(Q) &= f_i(Q_1^{K+1}, Q_2^{K+1}, \cdots, Q^{k+1}{}_n) = f_i(Q_1^{(k)}, Q_2^{(k)}, \cdots, Q_N^{(k)}) \\ &+ \frac{\partial f_i}{\partial Q_1} \bullet \Delta Q_1 + \frac{\partial f_i}{\partial Q_2} \bullet \Delta Q_2 + \cdots + + \frac{\partial f_i}{\partial Q_n} \bullet \Delta Q_n = 0 \end{aligned} \tag{1}$$

Given the following constraints on the above equation:

$$\frac{\partial f_i}{\partial Q_i} \bullet \Delta Q_i^{(k)} >> \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{\partial f_i}{\partial Q_j} \Delta Q_j^{(k)} \qquad i = 1, 2, ..., M \tag{2}$$

Equation (1) is simplified as:

$$\frac{\partial f_i}{\partial Q_i} \bullet \Delta Q_i^{(k)} = -f_i \tag{3}$$

So

$$\Delta Q_i = -\frac{\sum_{j=1}^{N} a_{ij} R_j \left| Q_j \right| Q_j - P_i - F_i}{2\sum_{j=1}^{N} a_{ij} R_j \left| Q_j \right| - \frac{dF_i}{dQ_i}} \tag{4}$$

Where, ΔQ_i is the corrected air volume of the circuit.

If Q_j (j=1, 2,..., N) has been assigned a certain initial value and the air volume balance equation is satisfied, but generally cannot satisfy the air pressure balance equation, then $a_{ij}\Delta Q_i$ is used to correct Q_j . However, when correcting Q_j, it will also cause changes in the airflow of the common branches between circuits, thereby affecting the convergence of other circuits. Therefore, it is necessary to repeatedly correct the circuits to achieve the required accuracy. The verification formula is as follows:

$$\left| Q_j^{(k+1)} - Q_j^{(k)} \right| \leq E \tag{5}$$

Where, E is the precision indicator, E>0.001.

2.2. Loop method computer program design

(1) Choose an independent circuit

To select an independent circuit, the first step is to obtain a tree diagram of the ventilation network and its corresponding residual tree diagram. Then, the chain branches of the residual tree diagram are added to the corresponding tree diagram one by one, forming a closed circuit with some of the branches in the tree diagram. Therefore, in order to select a reasonable independent circuit, the branches should first be sorted reasonably to ensure that the fixed air volume branch, the fan containing branch, and the high wind resistance branch are selected into the residual tree set. During the calculation process, the fixed branch and the fan containing branch should be ranked first, and the other branches should be arranged in descending order of wind resistance. The operation process of the program is equivalent to removing all branches in the wind network, leaving only all nodes, and then starting from the branch with the lowest wind resistance, adding branches to its original position on the wind network one by one to form the lowest tree. In the process of establishing the lowest tree, once a mesh or loop appears, the branch that finally forms the mesh or loop is the basic branch, that is, the highest wind resistance branch in the mesh or loop. Removing this branch will not form a mesh or loop, which is called "breaking the circle". A mesh or loop is based on a basic branch and extends in its direction until it forms a mesh or loop. The program stipulates that the direction of the mesh or loop is determined by the direction of the basic branch, so the branches in the mesh or loop that are consistent with the direction of the basic branch are called forward branches, and the branches in the opposite direction are called reverse branches, and they are recorded one by one.

(2) Calculate the natural wind pressure of the mesh or circuit

According to the input value of natural wind pressure, calculate the natural wind pressure of each mesh or circuit, and print the mesh or circuit numerical label as needed, including the mesh or circuit number, the number of branches within the mesh or circuit, the branch number and its direction, and the natural wind pressure value. The program allows natural wind pressure to appear on any branch.

(3) Fitting of wind pressure characteristic curve of fan

The wind pressure characteristics of a fan are generally characterized by a quadratic polynomial. If the data of three points on the input characteristic curve (the first point is the upper limit point for stable operation of the fan, the second point is the highest efficiency point, and the third point is the lower limit point), the quadratic spline interpolation method can be used to construct the expression formula for the characteristic curve. If the selected number of points is greater than three, non-linear fitting method is used.

(4) Initial value of air volume

For the mesh or circuit where the fixed air volume branch is located, the fixed air volume value can be directly assigned to the other branches of the mesh or circuit as the initial air cooling for iterative calculation. For fan branches, assign the airflow at the high-efficiency point on the fan curve to each branch of the mesh or circuit. The remaining basic branches are assigned 10, and then assigned to the remaining branches of the mesh or loop.

(5) Iterative calculation

Iterative calculation is the process of determining the natural distribution of airflow in a wind network, given the known wind resistance, natural wind pressure, and wind pressure characteristic curves of each branch. To ensure that the fixed air volume value remains unchanged, the computer program specifies that the mesh or circuit with a fixed air volume does not participate in the iteration. Since all branches in this type of mesh or circuit, except for the fixed air volume branch, are functional branches of other mesh or circuit branches, they actually participate in the iterative calculation. Iteration is based on the unit of mesh or loop, from the end of the chair until all mesh or loops reach the predetermined accuracy within the specified number of iterations.

(6) Calculate the resistance and wind resistance values of a fixed air volume vocabulary

Since the fixed air volume branch does not participate in the iteration, the resistance of the fixed air volume branch is calculated based on the wind pressure balance relationship of the circuit, that is

$$h_{fix} = -\sum_{\substack{j=1 \\ j \neq fix}}^{n} h_j, p_a \tag{6}$$

Then calculate the air resistance of the fixed air volume manifold:

$$R_{fix} = h_{fix} / Q_{fix9}^2, \quad N \bullet s^2 / m^8 \tag{7}$$

Where, R_{fix} is Fixed air volume branch air resistance value, $N \bullet s^2 / m^8$. h_{fix} is Fixed airflow branch resistance value, p_a . Q_{fix} is Fixed air volume value, m^3 / s . R_{fix}

is the wind resistance value that the branch must have to ensure a fixed air volume value remains unchanged.

3. Ventilation Network Example Solution

3.1. Experimental mine

Yuyang Coal Mine adopts the inclined shaft stage stone gate development method, and the industrial square, main and auxiliary inclined shafts, and return air adit are built in Jinjiyan. A secondary industrial square is set up in Yangdiwan, with a pair of auxiliary shafts (for pedestrian and gangue transportation) and a 310 main return air inclined shaft. The transportation roadway is located in the Maokou Formation limestone about 40 meters below the M12 coal seam. The mining method is inclined longwall layout. Medium thick coal seams are fully mechanized, while thin coal seams are high-grade conventional mining. The approved production capacity of the mine in 2007 was 1.05 million tons per year. The mine adopts a mixed ventilation method of extraction, with air intake from the main and auxiliary inclined shafts of Jinjiyan, Yangdiwan lifting, pedestrian inclined shaft, and coal transportation inclined shaft of Anding Power Plant, and air return from Jinjiyan and Yangdiwan air shafts. The Jinjiyan air shaft is equipped with two BD-II-8-No24 ventilation fans, one for backup and one for operation. Each fan is equipped with a synchronous motor with a rated power of 370KW and a speed of 742 r/min. The motor rotates in reverse direction. The fan was put into operation in February 2005. Currently, the blade installation angle of the fan is -5°, the longest ventilation route is 6649m, the fan exhaust volume is 5759m/min, the negative pressure is 1600Pa, and the motor output power is 219.04KW. The Yangdiwan wind shaft is equipped with two 2K58No24 ventilation fans, one in operation and one as backup. Each fan is equipped with a synchronous motor with a rated power of 450KW and a speed of 740 r/min, and the motor rotates in reverse direction. At present, the installation of the fan blades is 37.5°, the longest ventilation route is 8848m, the fan exhaust volume is 5944 m^3/min, the negative pressure is 1207Pa, and the motor output power is 204.72KW.

3.2. Comparison of software development and solution results

Based on the actual situation of Yuyang Coal Mine, the ventilation system diagram of Yuyang Coal Mine was obtained, as shown in Figure 1. According to the process of computer program design using the loop method, a ventilation network calculation software was developed, with the interface shown in Figure 2.

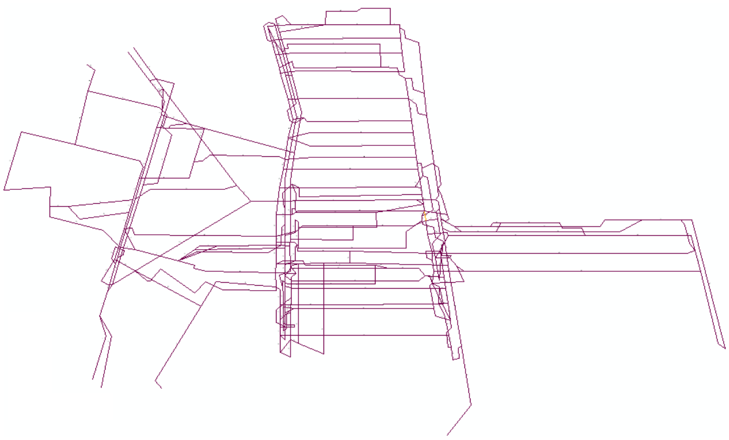

Figure 1. Ventilation system diagram of Yuyang Coal Mine

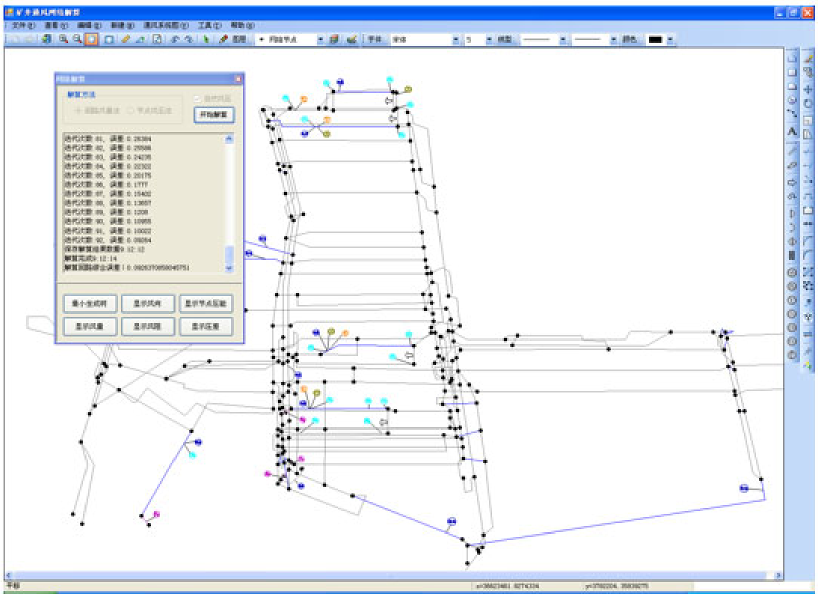

Figure 2. Ventilation network calculation function interface

After measuring the ventilation resistance parameters of Yuyang coal mine, the developed ventilation network calculation software was used to simulate the ventilation system of Yuyang mine. Firstly, based on the ventilation system diagram of the mine, the network diagram of the mine ventilation system is obtained through appropriate simplification. In this ventilation network diagram, there are 289 branches and 178 nodes. Then, the measured ventilation resistance parameters are entered into the corresponding branch attributes in the system, and the solution results are obtained through topology reconstruction, error checking, and iterative calculation. In the final calculation result, the total air volume of the mine is 211.9m^3/s, the wind pressure of Yangdiwan fan is 1755Pa, and the wind pressure of Jinjiyan fan is 2013Pa. The measured total air volume of the mine is 212.9 m^3/s, with an error of 0.47%. The wind pressure of Yangdiwan fan is 1676.2Pa, with an error of 4.5%, while the wind pressure of Jinjiyan fan is 1958.3Pa, with an error of 2.7%. The calculation errors of other main ventilation tunnels are shown in Table 1. According to Table 1, the maximum relative error of air volume at 36 measuring points in the main ventilation tunnels of Yuyang Coal Mine is 23.6%, the minimum is 0, and the average error is 3.6%.

Table 1. Calculation results of main ventilation tunnels in Yuyang Coal Mine

Lane branch number	Starting point	Ending point	Windage (Ns^2/m^8)	Measure volume(m^3/s)	Calculate volume(m^3/s)	Relative error(%)
1	1	2	.03412	49	49.7	1.41
2	2	3	.01993	72.9	74	1.49
3	6	7	.00364	82.7	84.8	2.48
4	14	15	1.9594	11.99	10.7	12.06
5	15	16	2.26225	9.1	9.3	2.15
6	16	18	.00227	66.4	67.2	1.19
7	19	20	.02285	118	115.3	2.34
8	20	21	.03507	118.15	118.2	0.04
9	1	2	.14355	23.9	24.2	1.24
10	28	29	.418007	22.1	21.8	1.38
11	29	30	.25093	15.35	15	2.33
12	36	37	.002023	40	39.7	0.76
13	42	43	.03985	75	78.7	4.70
14	44	45	.03031	94.4	93.7	0.75
15	49	50	.004211	58	54.8	5.84
16	51	52	.030966	18.7	16.2	15.43
17	59	60	.05811	22	23.6	6.78
18	1	61	.1783	36.7	36.6	0.27
19	61	62	.14023	30	29.9	0.33
20	67	68	.002211	16	15.3	4.58
21	75	76	.01025	7	7.1	1.41
22	76	37	1.9911	5.2	5.2	0.00
23	72	96	.44512	20.5	21.3	3.76
24	14	100	.0011	11	8.9	23.60
25	107	108	19.99	4.9	4.7	4.26
26	132	133	.02717	4.2	4.2	0.00
27	132	134	.18511	6.7	6.4	4.69
28	133	134	.1526	5.1	5.6	8.93
29	127	93	2.4111	4.6	4.4	4.55
30	29	150	.1276	7	6.8	2.94
31	150	151	16.9911	4.3	4.3	0.00
32	155	157	.00706	25	23.7	5.49
33	149	153	.04308	4.8	4.8	0.00
34	21	1	.000254	118.9	118.2	0.59
35	45	1	.00024	94	93.7	0.32
36	66	147	9.9911	4.95	4.9	1.02

4. Conclusion

A mine ventilation network calculation software was developed based on the loop air volume method, and a ventilation network calculation model using the loop air volume method was implemented. The measured total air volume of the Yuyang mine was 212.9 m^3/s, with an error of 0.47%. The average relative error of air volume at 36 measuring points in the main ventilation roadway is 3.6%. It indicates that the calculation of mine ventilation network can be carried out, and the calculation error is within the allowable range, which can be applied to actual mine ventilation network calculation.

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