Quantitative Evaluation Method and Application of Airflow Stability of Mine Ventilation System

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Abstract. A quantitative analysis method is proposed for airflow stability evaluation of complex ventilation networks. The influences of resistance change on airflow and its variation laws are analyzed by mathematical statistics method based on the simulation of airflow state in ventilation network. It is proposed that the airflow change rate is used as the quantitative evaluation index of airflow stability, and the sensitivity branches and dominant branches of ventilation system are determined by the airflow change rate matrix. A set of airflow direction discriminants of complex network is derived based on the deep analysis of the correlation among resistance, airflow and airflow change rate of branches. The results show that the stability quantitative analysis results and airflow direction discrimination results of this method are consistent with the results of computer simulation of airflow state, and the airflow direction discriminants can be applied to any complex network.

Keywords: Ventilation system, airflow stability, airflow change rate, quantitative evaluation, airflow direction decision.

1. Introduction

There is no clear definition of the air flow stability of the mine ventilation system. It is generally considered to be the air flow state of the ventilation system under external influence, reflecting the relatively stable air flow of the ventilation system and the ability to resist interference [1], it is related to the structure of the main ventilation system, the resistance of the roadway, the performance of the ventilator, the adjustment facilities, and the natural air pressure. The instability of the ventilation system can cause gas accumulation, circulating wind, and even accidents related to ventilation. Therefore, a stable ventilation system is very important to ensure safe production in the mine.

The corner joint branch is the most unstable branch in the network. A typical corner joint network can use the airflow direction decision to judge the flow direction [2, 3, 4], however, it is extremely difficult to discriminate the airflow direction of the complex angular network. Nowadays, the air flow sensitivity analysis method [5, 6, 7] and the ventilation network air flow state simulation calculation method [8, 9] are used to determine the sensitive branch and dominant branch of the network, and then evaluate the airflow stability and change degree of the ventilation system. The fuzzy comprehensive evaluation method [10, 11] is based on the evaluation index system to comprehensively evaluate the
stability and safety of the angle-connected branch airflow. Each evaluation method focuses on a certain aspect of the network element, and the evaluation results of the airflow stability of the ventilation system are different. The main problem is that the airflow direction of the unstable branch cannot be distinguished.

Based on the existing research results, this paper will use the method of "air flow simulation + mathematical statistics" to study the evaluation index and airflow direction judgment method of the ventilation system air flow stability, and verify its accuracy through case analysis.

2. Stability Evaluation Index of Ventilation System
Except for special cases, the ordinary branch only changes the air flow, while the angle-connected branch may be reversed by the interference of other branches. Through the in-depth numerical analysis of the air flow state, the air flow stability of the ventilation system can be evaluated.

2.1. Air flow sensitivity
When the resistance of branch $j$ in the ventilation network changes $\Delta r_j$, the air flow of branch $i$ will correspondingly change $\Delta q_i$, let:

$$
d_{ij} = \lim_{\Delta r_j \to 0} \frac{\Delta q_i}{\Delta r_j} = \frac{\partial q_i}{\partial r_j}
$$

(1)

We call $d_{ij}$ the sensitivity of the change in airflow of branch $i$ to the change in resistance of branch $j$, usually called "air flow sensitivity". Literature [5, 12] has given the calculation method of air flow sensitivity, so I won't repeat it.

2.2. Airflow change rate
The calculation found that: when the resistance of branch $j$ changes, the branch with a large basic air flow changes greatly, which affects the accuracy of $d_{ij}$ evaluation. Therefore, to evaluate the influence of branch $j$ on branch $i$, not only the absolute change in air flow but also the relative change must be considered. Considering the influence of relative changes in air flow, formula (1) can be modified as:

$$
d_{ij} = \lim_{\Delta r_j \to 0} \frac{\Delta q_i}{q_i^0 \Delta r_j}
$$

(2)

In the formula, $q_i^0$: when the network resistance is $R_0(r_1^0, r_2^0, \cdots, r_n^0)$, the natural air distribution of branch $i$, $m^3/s$; $R_0(r_1^0, r_2^0, \cdots, r_n^0)$: the basic resistance of the network, $Ns^2/m^8$; $n$: the number of branches of the network.

Taking $r_j = r_j^0 + \Delta r$, $r_i = r_i^0 (i = 1, 2, \cdots, n; i \neq j)$ as the resistance, the calculation results of the ventilation network show that [12], when $\Delta r$ is small the change of $q_{ij}$ is large. As $\Delta r$ gradually increases, $(r_j + \Delta r)$ changes almost linearly with $q_{ij}$, $d_{ij}$ is the slope of an approximate straight line, which can be considered as a constant. Among them, $q_{ij}$ is the air flow of branch $i$ when the resistance of branch $j$ changes. The formula (2) can be expressed as:

$$
d_{ij} = \frac{\Delta q_{ij}}{q_i^0 \Delta r} \approx \text{constant}
$$

(3)

Make:

$$
k_{ij} = d_{ij} \Delta r = \frac{\Delta q_i}{q_i^0}
$$

(4)
Then call \( k_{ij} \) the airflow change rate. From equation (4), it can be seen that no matter what value \( \Delta r \) takes, the order of \( k_{ij} \) value will not be changed. For calculation convenience, take \( \Delta q_i = q_i^0 - q_{ij} \), then:

\[
k_{ij} = \frac{q_{ij}^0 - q_{ij}}{q_i^0} \tag{5}
\]

Then, \( k_{ij} \) can be calculated as follows:

Step1 Use \( R^0(r_1^0, r_2^0, \ldots, r_n^0) \) as the resistance to solve the ventilation network, and find the air flow distribution \( Q^0(q_1^0, q_2^0, \ldots, q_n^0) \).

Step2 Set a resistance increment \( \Delta r \), set \( j = 1 \).

Step3 Use \( r_j = r_j^0 + \Delta r, r_i = r_i^0 (i = 1, 2, \ldots, n; i \neq j) \) as the resistance to solve the ventilation network, and find the air flow distribution \( Q(q_1j, q_2j, \ldots, q_nj) \).

Step4 Calculate \( k_{ij} = \frac{q_{ij}^0 - q_{ij}}{q_i^0} , (i = 1, 2, \ldots, n) \).

Step5 If \( j < n \), then make \( j = j + 1 \), turn step3.

The above calculation results form an \( n \times n \)-dimensional matrix, which is denoted as:

\[
K = \begin{bmatrix}
  k_{11} & k_{12} & \cdots & k_{1n} \\
  k_{21} & k_{22} & \cdots & k_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  k_{n1} & k_{n2} & \cdots & k_{nn}
\end{bmatrix} \tag{6}
\]

Call \( K \) the airflow change rate matrix.

3. Quantitative Evaluation Method of Ventilation System Stability

3.1. The influence of branch \( j \) on branch \( i \)

The air flow change rate \( |k_{ij}| \) is large, indicating that the change of the resistance of branch \( j \) has a great influence on branch \( i \).

3.2. Sensitive branch

Sum the rows of the air flow change rate matrix \( K \):

\[
x_i = \frac{1}{n} \sum_{j=1}^{n} |k_{ij}|, \quad (i = 1, 2, \ldots, n) \tag{7}
\]

Then \( x_i \) represents the sum of the effects of all branches on branch \( i \), indicating the sensitivity of branch \( i \) in the network, and a large \( x_i \) means that branch \( i \) is greatly affected by other branches and is an unstable branch.

3.3. Dominant branch

Sum the columns of the air flow change rate matrix \( K \):

\[
y_j = \frac{1}{n} \sum_{i=1}^{n} |k_{ij}|, \quad (j = 1, 2, \ldots, n) \tag{8}
\]

Then \( y_j \) represents the sum of the influence of branch \( j \) on other branches, indicating the dominance of branch \( j \) in the network, and a large \( y_j \) means that branch \( j \) has a large influence on network stability.
4. Airflow Direction Decision

According to formula (5), when \( k_{ij} > 0 \), the air flow of branch \( i \) decreases; when \( k_{ij} < 0 \), the air flow of branch \( i \) increases. Only when the air flow of branch \( i \) is reduced, can branch \( i \) have the possibility of reverse air flow. That is, when the air flow of branch \( i \) is reversed, \( k_{ij} > 0 \) is certain, but when \( k_{ij} > 0 \), the air flow of branch \( i \) may not be reversed. Therefore, the airflow direction of branch \( i \) cannot be determined according to equation (5). Make:

\[
 f_{ij} = \frac{k_{ij}}{k_{jj}} = \frac{q_{i}^{0} - q_{ij}}{q_{j}^{0} - q_{ij}} \tag{9}
\]

In the formula, \( q_{jj} \): the air flow of branch \( j \) itself when the resistance of branch \( j \) changes.

And when \( i = j \), \( f_{ij} = 1 \), so,

\[
 F = \begin{bmatrix}
 1 & f_{12} & \cdots & f_{1n} \\
 f_{21} & 1 & \cdots & f_{2n} \\
 \vdots & \vdots & \ddots & \vdots \\
 f_{n1} & f_{n2} & \cdots & 1 \\
\end{bmatrix}
\]

The following two situations can cause the airflow of branch \( i \) to reverse, that is, \( q_{ij} < 0 \).

1) The increase in the resistance of the branch \( j \) causes the air flow \( q_{ij} \) of the branch \( i \) and the air flow \( q_{jj} \) of the branch \( j \) to decrease simultaneously. When \( q_{ij} < 0 \), the air flow of the branch \( j \) is

\[
 0 \leq q_{jj} < q_{j}^{0}
\]

Substituting equation (9) to get \( f_{ij} > 1 \);

2) The decrease of the resistance of the branch \( j \) causes the decrease of the air flow \( q_{ij} \) of the branch \( i \), and the increase of the air flow \( q_{jj} \) of the branch \( j \). When \( q_{ij} < 0 \), the air flow of the branch \( j \) is

\[
 q_{j}^{0} < q_{jj} \leq q_{\text{max}j}
\]

Substituting equation (9) to get \( f_{ij} < q_{j}^{0} / (q_{j}^{0} - q_{\text{max}j}) \).

Based on the above analysis, we can get the discriminant formula that the resistance change of branch \( j \) causes the airflow of branch \( i \) to reverse:

\[
 \begin{cases}
 f_{ij} > 1 \\
 f_{ij} < f_{\text{max}ij}
\end{cases} \tag{10}
\]

Among them, \( \Delta r_{j} \): the change in resistance of branch \( j \), \( \text{Ns}^2/\text{m}^8 \); \( f_{\text{max}ij} = q_{j}^{0} / (q_{j}^{0} - q_{\text{max}j}) \). \( f_{ij} > 1 \) means that the resistance of branch \( j \) increases and the airflow of branch \( i \) is reversed, \( f_{ij} < f_{\text{max}ij} \) indicates that the resistance of the branch \( j \) decreases, causing the airflow of the branch \( i \) to reverse.

5. Case Analysis

In the mine ventilation system shown in Figure 1, the west wing is developed with an inclined shaft, the east wing is developed with a vertical shaft, the east and west wings are connected by a transportation stone gate (branch 5), and the coal from the east wing is transported to the west wing through a transportation stone gate.
Online: airflow (m³/s); offline: resistance (Ns²/m⁸)

**Figure 1.** Mine ventilation system.

The west wing fan (F_W) is responsible for the ventilation of the west wing, and the east wing fan (F_E) is responsible for the ventilation of the east wing and the transportation stone gate. The resistance and airflow of the roadway are shown in Table 1. After the transportation stone gate is penetrated, a complicated angle joint ventilation system is formed. Therefore, it is necessary to evaluate the airflow stability of the ventilation system and the possibility of the airflow reverse of the transportation stone gate.

| branch | r_0^j | q_0^j |
|--------|-------|-------|
| e1     | 0.0834 | 45.71 |
| e2     | 0.0548 | 70.69 |
| e3     | 0.035  | 73.25 |
| e4     | 0.0716 | 37.28 |
| e5     | 0.1902 | 8.43  |
| e6     | 0.1028 | 107.97|
| e7     | 0.16   | 81.69 |

5.1. Ventilation system stability

Suppose \( \Delta r = 0.1 \) Ns²/m⁸, according to the calculation method described in 2.2, the airflow change rate matrix is:

\[
K = \begin{bmatrix}
-0.236 & 0.164 & 0.235 & -0.069 & -0.007 & -0.025 & -0.017 \\
0.053 & -0.243 & 0.099 & 0.081 & -0.003 & -0.024 & -0.007 \\
0.092 & 0.121 & -0.259 & -0.036 & 0.007 & -0.007 & -0.026 \\
-0.103 & 0.444 & -0.192 & -0.158 & 0.005 & -0.058 & 0.013 \\
-0.823 & -0.922 & 2.123 & 0.321 & -0.058 & 0.122 & -0.149 \\
-0.001 & -0.005 & -0.002 & -0.001 & 0 & -0.044 & 0 \\
-0.002 & -0.003 & -0.013 & 0.001 & 0 & 0 & -0.039
\end{bmatrix}
\]

from equations (7), (8) and (9):

\[
X = [0.018 \ 0.073 \ 0.078 \ 0.139 \ 0.645 \ 0.008 \ 0.008]^{T}
\]

\[
Y = [0.187 \ 0.272 \ 0.418 \ 0.096 \ 0.011 \ 0.04 \ 0.036]^{T}
\]
According to the matrix \( X \), the branch sensitivity is arranged in ascending order \( \{5, 4, 1, 3, 2, 7, 6\} \), it can be seen that the diagonal branches 5 and 4 are unstable branches, especially \( x_5 \) is obviously larger than other branches are the most unstable branches; branches 7 and 6 (return air shaft) are the most stable branches.

According to matrix \( Y \), the order of branch dominance from large to small is \( \{3, 2, 1, 4, 6, 7, 5\} \), indicating that branches 3 and 2 are the key branches to ensure the stability of the airflow of the mine ventilation system.

According to the matrix \( K \), branch 3 has the greatest impact on branch 5. When branch 5 is affected by external influences and the airflow is unstable, the resistance of branch 3 can be increased to restore the airflow of branch 5 to normal.

5.2. Airflow direction discrimination

Only discuss the situation where the resistance increases and the airflow is reversed. According to matrix \( F \) and formula (10), we get:

1. \( f_{46} > 1 \), it shows that the resistance of branch 6 becomes larger, which will cause the airflow of diagonal branch 4 to reverse.

2. \( f_{51} > 1 \), \( f_{52} > 1 \) and \( f_{57} > 1 \), it shows that the resistance of branches 1, 2, and 7 will cause the airflow of diagonal branch 5 to reverse.

5.3. Calculation result test and analysis

Set the resistance of branch \( j \) to 0.01, 0.1, 1, 10, and 100 Ns\(^2\)/m\(^8\) in turn, and use the resistance shown in Table 1 to solve the ventilation network for other roadways. The air flow changes of branch 4 and branch 5 are shown in Figure 2 and Figure 3. In Figure 2, \( q_{4j} \) (\( j = 1, 2, \cdots, 7 \)) represents the air flow of branch 4 when the resistance of branch \( j \) increases. In Figure 3, \( q_{5j} \) (\( j = 1, 2, \cdots, 7 \)) represents the air flow of branch 5 when the resistance of branch \( j \) changes.

![Figure 2](image_url). Influence of resistance change on airflow of branch 4.
Figure 3. Influence of resistance change on airflow of branch 5.

1) It can be seen from Figure 2 and Figure 3: As the resistance of branch $j$ gradually increases, $\eta_j (j = 1,2,\cdots,7)$ and $q_{ij} (i = 4,5)$ change almost linearly. It is feasible to treat $k_{ij}$ as a constant.

2) It can be seen from Figure 2 that as the resistance of branch 6 increases, the air flow of branch 4 gradually decreases and reverses; it can be seen from Figure 3 that as the resistance of branches 1, 2 and 7 increase, the air flow of branch 5 gradually reduce and reverse, it is consistent with the discriminant result of equation (10).

6. Conclusions
The method of "air flow state simulation + mathematical statistics" is used to study the air flow stability of the ventilation system. The air flow change rate is proposed as an evaluation index, the air flow change rate matrix is established, and the quantitative evaluation method and air direction judgment of the stability of the ventilation system are given. The following conclusions are drawn:

1) The air flow change rate matrix can judge the sensitive branch and dominant branch of the network, and the judgment accords with the actual situation of the mine.

2) The airflow direction decision is suitable for the air direction discrimination of any complex ventilation network.

3) For the example, the transportation stone gate (branch 5) is the branch with the most unstable airflow, and the resistance of branches 1, 2, or 7 may cause the airflow to reverse. However, the calculation method of resistance when the airflow is reversed needs further research.

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References
[1] WANG Chongxian, LI Xuguo, TAN Bo. Influencing factors of air quantity stability of ventilation system in coal mine[J]. Journal of China Coal Society,2008,33(8):931-935.
[2] ZHOU Shining. Some basic characters of mine ventilation network and their application to determining airflow direction[J]. Journal of China Coal Society, 1982(03):3-11.
[3] JIA Jinzhang1, LIU Jian1, SONG Shousen. Numerical analysis of ventilation system stability[J]. Mining Safety & Environmental Protection, 2003(06):10-11.
[4] KRACH A. Determining Diagonal Branches in Mine Ventilation Networks[J]. Archives of Mining Sciences, 2014,59(4):1097-1105.
[5] JIA Jinzhang1, LIU Jian1, SONG Shousen. Numerical analysis of ventilation system stability[J]. Mining Safety & Environmental Protection, 2003(06):10-11.
[6] WANG Conglu, WU Chao, WANG Weijun. Application of Lyapunov theories in mine ventilation...
system stability analysis [J]. Journal of Safety Science and Technology, 2005, 1(4): 46-49

[7] SONG Zeyang, LI Xuechuang, QI Wenyu, et al. An Approach for Quantification of Determination of Mine Ventilation Stability [J]. China Safety Science Journal, 2011(09): 121-126.

[8] WEI Shangyin, CHANG Xintan, LI Ruming. Stability analysis of complex ventilation system [J]. Journal of Xi’an University of Science and Technology, 2003(02): 119-122.

[9] Semin L. M. A, Levin Yu., Stability of air flows in mine Ventilation networks [J]. Process Safety and Environmental Protection. 2019, 124: 167-171.

[10] CHEN Kaiyan, WANG Chao. Variable weight comprehensive evaluation for mine ventilation system reliability [J]. Journal of Mining & Safety Engineering, 2007, 24(1): 37-41.

[11] LU Gang, HAN Keqi, XIAO Guibin. Fuzzy integrated evaluation for reliability of mine ventilating system [J]. Journal of Mining & Safety Engineering, 2008, 25(2): 244-247.

[12] JIA Tinggui, WANG Shugang, QU Guona, et al. Research on the Influence of Airway Sensitivity on the Airflow Stability of Mine Ventilation System [J]. Journal of Mining & Safety Engineering, 2012, 029(001): 140-143.