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Analysis of mine's air leakage based on pressure gradient matrix between nodes*

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Abstract Air leakage may significantly affect the effectiveness of mine ventilation by increasing the cost of ventilation and arousing problems for ventilation management. Furthermore, air leakage may accelerate the process of coal spontaneous combustion and cause gas explosion, thus greatly threatens the safety of coal production. The estimation of air leakage, therefore, have great practical significance. For any ventilation system of coal mines, there is a defined pattern of pressure gradient which drived the mine air to flow in the network, drives possible air leakage to go shortcut as well. Air leakage may occur through ventilation structures such as ventilation doors and fractures of the surroundig coal and rock of airways. A concept and the relevent calculation method of the pressure gradient matrix was put forward to assist the analysis of potential air leakage routes. A simplified example was used to introduce the application principle of pressure gradient matrix in identifying all the potential air leaking routes, which offers a deeper understanding over the ventilation system and the prevention of coal spontaneous combustion.

Keywords air leakage, pressure gradient, porous media, air permeability

Introduction

For any ventilation system of mines, nodes serve as junctions of relevent airways and thus satisfy the flow balance equation, namely conservation of mass[1]. However, for a practical ventilation system with the airways' surrounding rock permeable for air to some extent, air leakage may occur. Air leakage may significantly affect the effectiveness of mine ventilation due to an increasing cost of ventilation and arousing problems for ventilation management. Furthermore, air leakage may accelerate the process of coal spontaneous combustion and cause gas explosion, thus greatly threaten the safety of coal production[2-4]. To a certurn extent the coal and rock surrounding nodes can be treated as porous media, which allow the air pressure gradient to act as the driving force to cause the air leakage following Darcy's law of fluid mechanics in porous media[5]. The pressure gradient matrix of nodes describes the pressure gradient between each pair of nodes, which can be employed to analyze the potential air leakage routes. Furthermore, combining the analysis of air permeability within coal and rock mass between nodes, the pressure gradient matrix of nodes can even be used to estimate the intensity of air leakage, which provides a better understanding for ventilation management and working safety of coal mine.

1 Pressure gradient matrix between nodes

1.1 Definition and calculation of node's pressure value

Under normal conditions, the ventilation of coal mines can be treated as a steady-state process with the ventilation resistance, airflow rate and pressure change being constant. As a direct consequence of energy conservation law, the ventilation pressures dissipate from the inlet of mine to any node in the lower reaches are equal to each other no matter what route the air-flow

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follows. Taking the air pressure at mine's outlet as the base-pressure, pressures at other nodes in the ventilation system are defined as the relative pressure over the base-pressure. Then, the ventilation pressure at a node is positive for both an exhausted ventilation system and a pushing ventilation system. It equals the pressure dissipated by airflow from that node to the outlet of mine, as shown in equation below:

$$P_i = \sum_{j=1}^{n} R_j Q_j^2, \tag{1}$$

where, P_i is the pressure at node i; R_j and Q_j are respectively the air resistance and the quantity of airflow in lane j, which represents all branches along the flow path of air.

For instance, given a ventilation system shown as Fig.1, the pressure at node 4 can be computed as:

$$P_4 = R_9 Q_9^2 + R_{11} Q_{11}^2 = R_7 Q_7^2 + R_{10} Q_{10}^2 + R_{11} Q_{11}^2 = R_7 Q_7^2 + R_6 Q_6^2 + R_8 Q_8^2$$

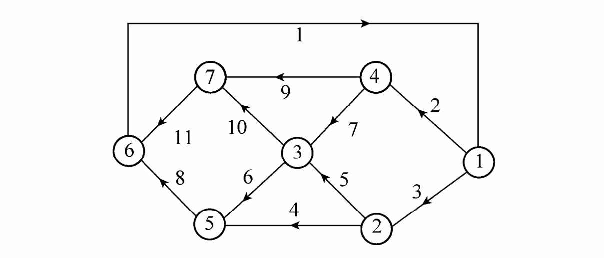

Fig.1 Ventilation network

1.2 Definition and calculation method of pressure gradient matrix between nodes

For an arbitrary ventilation system, ventilation pressures at nodes are usually different. In the steady-state process, the pressure difference between a pair of interrelated nodes is in a balance with the air-flow rate in the airway defined by the nodes. A pair of arbitrary nodes do not always define an airway. If the coal or rock mass between nodes is very compact, namely their permeability is very low so as to be regarded as impermeable, no air leakage between the nodes exists. If nodes under consideration are close enough and fractures in the rock are well developed due to minging activities, air leakage will occur through the surrounding coal or rock mass of the nodes. Usually the velocity of air leakage is very low, so air leakage can be deemed as satisfying the Darcy's law[5], which describes the flow state of fluid mass in porous media. The equation is shown as below:

$$v = -k \frac{\mathrm{d}p}{\mathrm{d}l}, \tag{2}$$

where, v is the seeping velocity, namely the velocity of air leakage; k is the coefficient of permeability; dp is the pressure difference between two nodes; dl is the distance between tow nodes.

Eq.(2) means that the velocity of air leakage between nodes is in direct ratio to the pressure difference and the coefficient of permeability, whereas in a reverse ratio to the distance.

Let J_{ij} denote the pressure gradient between node i and node j, then

$$J_{ij} = \frac{\mathrm{d}p}{\mathrm{d}l} = \frac{(P_i - P_j)}{L_{ij}}, \tag{3}$$

where, P_i, P_j are the pressure value of node i and node j respectively; L_{ij} is the distance from node i to node j.

When i, j vary from 1 to N, L_{ij} defines a matrix:

$$\boldsymbol{L} = \begin{pmatrix} L_{11} & \cdots & L_{1n} \\ \vdots & \vdots & \vdots \\ L_{n1} & \cdots & L_{nn} \end{pmatrix}.$$

Matrix $\boldsymbol{L}$ is named as distance matrix between nodes. In the same way, J_{ij} defines a matrix:

$$\boldsymbol{J} = \begin{pmatrix} J_{11} & \cdots & J_{1n} \\ \vdots & \vdots & \vdots \\ J_{n1} & \cdots & J_{nn} \end{pmatrix}.$$

Matrix $\boldsymbol{J}$ is named as pressure gradient matrix between nodes in a ventilation system.

2 Application principle of matrix *J* in the analysis of air leakage

Let K_{ij} denote the coefficient of permeability of the coal or rock between node i and node j, When i, j vary from 1 to N, K_{ij} denotes a matrix:

$$\boldsymbol{K} = \begin{pmatrix} K_{11} & \cdots & K_{1n} \\ \vdots & \vdots & \vdots \\ K_{n1} & \cdots & K_{nn} \end{pmatrix}.$$

Matrix $\boldsymbol{K}$ is named as seeping matrix between nodes. Let

$$\boldsymbol{V} = \begin{pmatrix} V_{11} & \cdots & V_{1n} \\ \vdots & \vdots & \vdots \\ V_{n1} & \cdots & V_{nn} \end{pmatrix},$$

where, $V_{ij} = -J_{ij} K_{ij}$, then

$$\boldsymbol{V} = -\boldsymbol{J}\boldsymbol{K}^{\mathrm{T}}, \tag{4}$$

where, K^{T} is the transpose of matrix $\boldsymbol{K}$.

From Eqs.(2) and (3), V_{ij} is the velocity of air leakage, so V denotes the velocity matrix of air leakage.

Matrix $\boldsymbol{J}$ can be calculated with known ventilation parameters, but matrix $\boldsymbol{K}$ is difficult to obtain. In fact, most of coal and rock mass between nodes can be deemed as impermeable, thus the coefficient of permeability can be taken as zero. On the other hand, the permeability of coal and rock mass is affected by the mining activities, so matrix ***K*** should be a sparse matrix. Which element of ***K*** can be thought greater than zero depends on the constructing environment of coal strata, the layout of mining face and tunnelling face in a ventilation system, as well as the history of excavation of coal mine.

With the information of seeping matrix ***K*** between nodes inaccessible, pressure gradient matrix ***J*** becomes the only clue to estimate the potential air leaking routes. Deriving from the Darcy's law, air leakage becomes more possible between two nodes with more pressure gradient. Given pressure gradient matrix ***J*** and seeping matrix ***K*** between nodes, the velocity matrix ***V*** of air leakage can be worked out immediately from Eq.(4), with which not only the potential air leaking routes but also the intensity of air leakage can be computed.

3 Case analysis

Given a ventilation network system as shown in Fig.1, which includes 11 airways and 7 nodes, with the main fan located at airway 1. Basic parameters of each airway is shown in Table 1.

Table 1 Basic information

Lane number	Start node	End node	Ventilation resistance(N • s^2/m^8)	Airflow (m^3/s)	Air pressure(Pa)
1	6	1	2.246 49	29.135	−748.330
2	1	4	1.471 50	14.168	295.376
3	1	2	1.373 40	14.967	307.659
4	2	5	4.120 20	7.079	203.473
5	2	3	1.177 20	7.888	73.247
6	3	5	0.784 80	13.031	133.277
7	4	3	0.981 00	9.337	85.530
8	5	6	0.588 60	20.110	238.052
9	4	7	5.886 00	4.830	137.348
10	3	7	2.943 00	4.193	51.761
11	7	6	3.924 00	9.024	319.569

Distance matrix between nodes is shown in Table 2.

Table 2 Distance matrix between nodes km

Node	1	2	3	4	5	6	7
1	0	0.2	0.4	0.2	0.5	0.7	0.5
2	0.2	0	0.3	0.3	0.4	0.6	0.6
3	0.4	0.3	0	0.3	0.3	0.5	0.3
4	0.2	0.3	0.3	0	0.6	0.6	0..4
5	0.5	0.4	0.3	0.6	0	0.3	0.5
6	0.7	0.6	0.5	0.6	0.3	0	0.3
7	0.5	0.6	0.3	0.4	0.5	0.3	0

The air pressure (Table 3) at each node can be calculated from Table 1.

Table 3 Node's pressure value Pa/m

P_1	P_2	P_3	P_4	P_5	P_6	P_7
748.33	440.66	367.41	452.95	238.05	0	319.57

Pressure gradient matrix(Table 4) calculated from Table 2 and Table 3.

The pressure gradient matrix of nodes (Table 4) shows that the values of J_{12} and J_{14} are relatively large, which means that, besides the existing airway 3 from node 1 to node 2 and airway 2 from node 1 to node 4, potential air leaking routes may exist if the permeability of the surrounding rock is siginificant, even if within a relatively small region. The air leakage problem in the surrouding rock along an airway usually takes place in working faces due to the cave-in gob area. The larger pressure gradient between the intake and return air in a working face exists, more air may penetrate into a deeper region of the gob. The value of J_{16} is also greater than 1, which implys a possibility for air to leak from node 1 (the atmosphere) to node 6 (outlet of air from the mine). It should be noticed that the possible air leaking from node 1 to node 6 is named as the surface leakage which goes through ventilation structures at the mouth of return shaft to seal the underground system of the mine. For a pair of nodes with significant pressure difference, similar analysis may apply to considering the possibilities of air leakage.

Table 4 Nodes' pressure gradient matrix

Node	1	2	3	4	5	6	7
1	0	1.538 3	0.952 3	1.476 8	0.476 1	1.069 0	0.639 1
2	−1.538 3	0	0.244 2	−0.041 0	0.508 7	0.734 4	0.201 8
3	−0.952 3	−0.244 2	0	−0.028 5	0.444 3	0.734 8	0.172 5
4	−1.476 8	0.041 0	0.028 5	0	0.358 2	0.754 9	0.343 4
5	−0.476 1	0.508 7	−0.444 3	−0.358 2	0	0.793 5	−0.163 0
6	−1.069 0	−0.734 4	−0.734 8	−0.754 9	−0.793 5	0	−1.065 2
7	−0.639 1	−0.201 8	−0.172 5	−0.343 4	0.163 0	1.065 2	0

More importantly, no matter the pressure gradient between a pair of nodes is, air leakage may still be significant with the permeability of coal and rock mass being good. Mining activities may cause the permeability of rock and coal in the vicinity of work face to increase dramatically, thus give rise to serious problems of air leakage.

4 Conclusions

(1) Air leakage in coal mines is a shortcut of airflow, which may cause serious problems in coal spontaneous combustion and undesired gas flow.

(2) based on an analysis of mine ventilation, a concept and the relevent calculation method of pressure gradient matrix is put forward to assist identify potential routes of air leakage in the system, which has great importance for coal mine to enforce the ventilation management, enhance ventilation efficiency, save ventilation cost and prevent the spontaneous combustion.

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