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Graph theory and its application in optimization of gas drainage system in coal mine
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Abstract
Gas drainage is an important gas treatment measure. With changing the location and gas drainage quantity of the system, some reasonless phenomena would occur. Hence, the system must be optimized. According to the relation of graph theory and gas drainage system, the gas drainage system of Zhao Gezhuang mine is optimized by graph theory and the resistances are calculated. After optimization, the drainage resistance is equally distributed, which increases the quantity of gas drainage from coal mine, improves the efficiency and reliability of mine gas drainage system and enhances the safety of the mine; so the firm foundation of the gas utilization is established and the virtuous cycle of "drainage-usage -safety production" and comprehensive gas control are well realized. It shows that the graph theory can be well applied in gas drainage system optimization.

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Keywords: graph theory; gas drainage system; optimization; resistance.

1. Introduction
Gas drainage is an important gas treatment measure; the main purpose is to prevent the gas exceeding the limit, to ensure coal mine safety, so an effective gas drainage system will be more helpful for the realization of the mine gas management goal. In the initial stage of mine operation, gas drainage system is consistent with the principle of gas drainage. With changes of drainage place and drainage quantity, the drainage system will bring the reasonless phenomena, so the system must be optimized. The optimization work of the existing gas drainage pipeline is mainly concentrated in the drainage's negative pressure, drainage velocity, drainage volume of drainage system, optimization design of drainage pipe diameter and local drainage pipeline distribution, according to the resistance distribution. Compared with mine ventilation system, the drainage system optimization is simple, and it is the daily work. So the optimization work of drainage pipeline system also depend mainly on the personnel decision experience in planning and design, which results in that optimization decision show very subjective randomness, lack of theoretical basis. So the design is often conservative, which increase the unnecessary setup in pipeline, increase the construction quantity. firstly, it is not reasonable from an economic view, secondly, because drainage pipeline system are not reasonable, gas drainage efficiency is low, which must affect the safe production in the working face, so the simple application of the drainage pipeline network system optimization decision method is particularly necessary.

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2. The graph theory analysis on mine gas drainage system

2.1. Mine gas drainage system

Mine gas drainage system is the general term of drainage pipe network, drainage mode and drainage method. The mine gas drainage system usually is a three-dimensional diagram, which reflects the spatial location, flow quantity, flow direction, drainage method and drainage mode of the drainage pipeline. The mine gas drainage system can objectively reflect the actual situation of mine drainage system [1]. In any mine drainage system, the gas in all the branch pipeline forms a directed communication system, according to their rendezvous structural form. In this system, under the action of negative pressure of the drainage pump, the gases in the local gas drainage place are drained, and the gases flow in the drainage pipeline, which ensure good weather and safety conditions. Gas flow in pipeline abides by the certain rules, drainage flow in all the drainage pipeline is not up to people's subjective decision. In mine drainage network, the rules are abided by as follow: ① the law of energy conservation; ②the resistance law; ③the flow balance law. So people know that how to use flow controlling the pipeline flow to meet production needs.

2.2. The basis concept on graph theory

In graph theory, A graph G is defined as a dual pair (V, E), namely, G = (V, E), V= , V is the node set of graph G; E= , E is the edge set of graph G. Therefore, graph is composed of node set and branch set, its essence is the connection relation between nodes and branches. the namely the topological relationship.

According to the different standard, the graph can be divided into different types, if the V and E are finite set, the graph G is finite graph, otherwise is infinite graph. If the dual pair( V, E ) is orderly, namely, the graph is composed of node and directed branch, which is called a directed graph, otherwise called undirected graph. The graph with directed branches and undirected branches is called mixed graph. The graph with rings and without the parallel branches is called simple graph. The graph with the parallel branches is called multiple graph. When graph with point and branch is used to reveal the specific value relations, weight function can be defined in E or V, thus the weight graph is formed. In the graph, if the at least road is existed between any two nodes, the graph is called the connected graph [2-6].

2.3. The graph theory analysis on mine gas drainage system

The mine gas drainage system graph also is the graph with node set and edge set, G = ( V, E ), V is the node set, V=m; the E is the edge set, E=n. If each node location is not considered, according to link relationship between drainage pipeline and intersection point, the connecting edge eK=(ui,vi) make the graph have no-intersecting edge or intersecting edge is at least(except nodes). The graph G is a planar graph, which can fully reflects line structure of gas flow in the drainage system. Because the mine gas drainage system is a directed connected system, so in the corresponding gas drainage network, gas flow direction calibrates the corresponding edge direction, its directed edges is called arc. If the parameters (such as resistance, flow, length, basal area etc) in the gas drainage pipeline are corresponding to the edge, then a mine gas drainage network graph is formed.

2.4. The drawing of mine drainage network

According the association relationship between the node and arc, the node of any gas intersection points in corresponding drainage system join in the arc one by one, the adjacent nodes can be obtained and each adjacent node position is moved continuously, which make the arc intersect as much as possible in the node outside. When the node and arc join in the graph in turn, the plan graph can be obtained, namely mine drainage network graph[7-9]. So the drainage network graph is a directed connected graph with weight, each branch has a definite direction, each branch has flow, resistance value, at least a directed path is existed between any two nodes. According to the graph theory, drainage networks graph and drainage system graphs are isomorphic, which all have the same number of nodes and branches, the relationship between nodes and branches is corresponding to each other, the corresponding branches have the same weight. The drainage network characteristic is that the graph itself only need reflect the number of nodes and branches and connection relation between the nodes and branches. There is no relation between the node position, branch length, location of pipeline intersection point and the actual length of pipeline. The length of the pipeline is only as a weight of a drainage network graph and is not reflected by the branch lengths.
In a word, drainage network graph is the drainage system graph expressed by a graph concept and the method, which can analyze mine drainage system and solve the problems such as drainage flow and the resistance. So the drainage system optimization in fact can be seen as a drainage network graph optimization.

3. Application of graph theory in mine gas drainage system

From the above analysis, graph theory can be used in mine gas drainage system optimization, so the graph theory is applied to the gas drainage system optimization in Zhaogezhuang mine etc.

3.1. General situation of gas drainage system in Zhaogezhuang mine

To meet the demand of gas control, the Zhaogezhuang mine (mine with high gas) has built a permanent ground gas drainage system and underground mobile drainage system. Gas drainage system in Zhaogezhuang mine has been used for many years, with the increase of mining depth, the widening of the width and changes of workface, there are mainly the several problems in gas drainage pipeline as follow: ①The change of gas drainage quantity, namely the gob gas drainage quantity is in the reduction, the threat degree of emission gas on safety production is decreased gradually, and the proportion of the gas drainage quantity and excretion quantity changes. ②With the increase of mining depth, the widening of the work face width and change of workface, gas drainage pipeline length increases, and the drainage resistance increases, which result that the drainage system resistance distribution is not reasonable, and which affect the effect of gas drainage. ③gas drainage pipeline was used for years, there are the presence of phenomena such as rust leakage, deposition of coal dust, which affects drainage effect. ④the increase of new gas drainage drilling field changes the reasonable distribution of the original drainage system. Therefore, the existing drainage system has many problems, so the original drainage system must be optimized, to improve drainage efficiency, reliability and mine safety.

3.2. The resistance calculation of gas drainage system

The gas drainage system in Zhaogezhuang mine now includes the following place: 10 level west wing, 11 level west wing, 12 level west wing, 8east 3dao gob, 9east 3dao gob, 9east 4dao gob, 11 level east wing, 12 level east wing, 13 level east wing. Now the whole drainage system resistance is calculated, such as listed in table 1.

| Numbering | location                  | Flow/ | diameter / | Length/ | Concentration/ | friction resistance/ | local resistance/ | Total resistance/ |
|-----------|---------------------------|-------|------------|---------|----------------|---------------------|------------------|------------------|
|           |                           | m³/min| mm         | m       | %              | Pa                  | Pa               | Pa               |
| 1         | Shaft pipe                | 22    | 419        | 710     | 33             | 113                 | 16.9             | 129.9            |
| 2         | new831, new931, new031   | 22    | 377        | 868     | 33             | 237                 | 36               | 273              |
| 3         | 10 level west             | 6.03  | 159        | 380     | 35             | 570                 | 85.5             | 655.5            |
| 4         | new031-west 5dao         | 8.87  | 159        | 530     | 47             | 1614.5              | 242.2            | 1856.6           |
| 5         | 11 level west, 115 pipe  | 7.1   | 159        | 720     | 40             | 1460                | 219              | 1679             |
| 6         | 141pipe, 241pipe         | 8.87  | 219        | 581     | 47             | 357                 | 54               | 411              |
| 7         | 241-12west               | 0.72  | 219        | 310     | 50             | 1.24                | 0.186            | 1.426            |
| 8         | 241-12dao east           | 8.15  | 219        | 600     | 47             | 311.3               | 47               | 358              |
| 9         | 12 level west             | 0.72  | 159        | 510     | 50             | 10                  | 1.5              | 11.5             |
| 10        | 332pipe                  | 4     | 159        | 600     | 56             | 352.4               | 53               | 405.4            |
| 11        | 13 level west             | 80    | 219        | 1800    |                | 1800                |                  |                  |
| 12        | 13 level east             | 4     | 159        | 310     | 56             | 182                 | 27.3             | 209.3            |
| 13        | 12 level east             | 0.15  | 159        | 390     | 30             | 0.37                | 0.056            | 0.43             |
| 14        | 232pipe                  | 4     | 159        | 270     | 40             | 174                 | 26.1             | 200.1            |
| 15        | 11 level east             | 4     | 108        | 850     | 40             | 4334                | 780.1            | 4984.1           |
| 16        | 8, 9 level gob            |       |            |         |                |                     |                  |                  |
The mine gas drainage system is simplified by application of mine gas drainage network graph theory, which is shown as Fig.1(a). Through the calculation and analysis on gas drainage system, there are 7 independent drainage loops in mine gas drainage system, according to gas flow rule in mine drainage network, the drainage network graph can be obtained as Fig. 1(b).

It is show in Fig. 1(b) that the 7 independent drainage loops are R1 (including 3, 2, 1), R2 (including 5, 2, 1), R3 (including 9, 7, 6, 4, 2, 1), R4 (including 13, 8, 6, 4, 2, 1), R5 (including 11, 10, 8, 6, 4, 2, 1), R6 (including 12m 10, 8, 6, 4, 2, 1), R7 (including 16, 15, 14, 8, 6, 4, 2, 1).

![Diagram](image)

Fig. 1. (a) Simplified diagram of gas drainage system; (b) Drainage network diagram.

The resistance of the independent drainage loops is shown as follow:

\[ H_{R1} = 655.5+273+129.9 = 1058 \text{ Pa} \]
\[ H_{R2} = 1679+273+129.9 = 2082 \text{ Pa} \]
\[ H_{R3} = 11.5+1.426+411+1856+273+129.9 = 2683 \text{ Pa} \]
\[ H_{R4} = 0.43+358++411+1856+273+129.9 = 3028 \text{ Pa} \]
\[ H_{R5} = 405+358++411+1856+273+129.9 = 3433 \text{ Pa} \]
\[ H_{R6} = 209+405+358++411+1856+273+129.9 = 3642 \text{ Pa} \]
\[ H_{R7} = 4984+200+358++411+1856+273+129.9 = 8212 \text{ Pa} \]

From the calculation results of the 7 independent drainage loops, it can be found that the resistance in R3, R4, R5, R6, R7 is far more than in R2 and R1. The factor resulting to resistance increase in R3, R4, R5, R6, R7 is the 4 pipe. As long as the resistance of No4 pipe reduces, the resistance in R3, R4, R5, R6, R7 also reduces. The factor resulting to resistance increase in R7 is not only the No4 pipe, but also the No15 pipe. The No15 pipe controls the drainage in 2132 gob, 2222 gob, 9east3dao gob, 9east 4dao gob, 8east3dao gob. The gas drainage quantity in 9east3dao gob, 9east 4dao gob and 8east3dao gob is very little, the gas drainage quantity in 2132 gob and 2222 gob also decrease gradually. From the gas drainage time, drainage cost and other aspects, the No15 pipe need not be replaced, but the coal dust must be eliminated. In a word, the problem in Zhaogezhuang mine gas drainage system is that the local resistance is too large. For local resistance problem, it can be solved by replacing a larger pipe diameter.

3.3. Optimization position

Through using drainage network to optimize the drainage system, it can be obtained that No 4 pipe need to be replaced by the pipe with the larger diameter; other place does not need to be replaced. The calculation of gas drainage pipe diameter can be used the following formula [4]

\[ D = 0.1457 \sqrt{\frac{Q}{u}} \]  

(1)

where \( D \) is inner diameter of gas drainage pipe, m; \( Q \) is gas flow in gas drainage pipe, m³/min; \( u \) is the average flow velocity, m/s;
The flow velocity in 141 pipe and 24 pipe is 6.7m/s, so the flow velocity in No4 pipe should be litter than 6.7m/s. when the flow velocity in No4 pipe is 6.7m/s, the gas flow Q is 14.87m³/min, so the diameter D is 0.217m, namely, the diameter in No4 pipe should be 217mm.

3.4. The resistance calculation after optimization

When the gas in 13 level west drainage systems (underground mobile drainage) is drained into the main drainage system, namely the gas flow is the largest and the resistance is most, the calculated resistance is listed such as in table 2.

| Numbering | location               | Flow/ m³/min | diameter / mm | Length/ m | Concentration/ % | friction resistance/ Pa | local resistance/ Pa | Total resistance/ Pa |
|-----------|------------------------|--------------|---------------|-----------|-----------------|------------------------|----------------------|----------------------|
| 1         | Shaft pipe             | 28           | 419           | 710       | 33              | 183                    | 27                   | 211                  |
| 2         | new831, new931, new031| 28           | 419           | 868       | 33              | 380                    | 57                   | 437                  |
| 3         | 10 level west          | 6.03         | 159           | 380       | 35              | 570                    | 86                   | 656                  |
| 4         | new031-west 5dao       | 14.87        | 219           | 530       | 47              | 623                    | 94                   | 717                  |
| 5         | 11 level west, 115 pipe| 7.1          | 159           | 720       | 40              | 1460                   | 219                  | 1679                 |
| 6         | 141pipe, 241pipe       | 14.87        | 219           | 581       | 47              | 578                    | 87                   | 665                  |
| 7         | 241-12west             | 0.72         | 219           | 310       | 50              | 1.24                   | 0.2                  | 1.44                 |
| 8         | 241-12dao east         | 14.15        | 219           | 600       | 47              | 504                    | 76                   | 580                  |
| 9         | 12 level west          | 0.72         | 159           | 510       | 50              | 10                     | 1.5                  | 11.5                 |
| 10        | 332pipe                | 10           | 159           | 600       | 56              | 570                    | 86                   | 656                  |
| 11        | 13 level west          | 6            | 219           | 1800      | 30              | 526                    | 79                   | 605                  |
| 12        | 13 level east          | 4            | 159           | 310       | 56              | 182                    | 27                   | 209                  |
| 13        | 12 level east          | 0.15         | 159           | 390       | 30              | 0.37                   | 0.06                 | 0.42                 |
| 14        | 232pipe                | 4            | 159           | 270       | 40              | 174                    | 26                   | 200                  |
| 15        | 11 level east          | 4            | 108           | 850       | 40              | 4334                   | 650                  | 4984                 |
| 16        | 8, 9 level gob         |              |               |           |                 |                        |                      |                      |

Through the analysis in Fig.1(b), the resistances of the independent drainage loops are shown as follow:

- \( H_{R1} = 656 + 437 + 211 = 1304 \) Pa
- \( H_{R2} = 1679 + 437 + 211 = 2327 \) Pa
- \( H_{R3} = 11.5 + 1.44 + 665 + 717 + 437 + 211 = 2043 \) Pa
- \( H_{R4} = 0.42 + 580 + 665 + 717 + 437 + 211 = 2610 \) Pa
- \( H_{R5} = 605 + 656 + 580 + 665 + 717 + 437 + 211 = 3871 \) Pa
- \( H_{R6} = 209 + 656 + 580 + 665 + 717 + 437 + 211 = 3475 \) Pa
- \( H_{R7} = 4984 + 200 + 580 + 665 + 717 + 437 + 211 = 7794 \) Pa

From the flow quantity and flow velocity, the diameter in No4 pipe should be 217mm; from the drainage system resistance, the diameter in No4 pipe also should be 217mm, so the diameter in No4 pipe should be 217mm.

Considering the total resistance of gas drainage system, the maximum resistance should be the total system resistance, which is 7794Pa.

4. Conclusions

(1) The results showed that, the graph theory has a good association relationship with the mine gas drainage system, which can be well applied in optimization design of mine gas drainage system.

(2) The gas drainage resistance distribution of the existing system is not reasonable, the drainage resistance in No4 pipe is too large, and the reason is that diameter is too small, so it should be replaced by the pipeline with diameter 217mm.

(3) After optimization of the gas drainage system, the drainage resistance distribution is reasonable, which increases the gas drainage quantity from coal mine, improves the efficiency and reliability of mine gas drainage system, enhances the
mine safety, so the firm foundation of the gas utilization is established and the virtuous cycle of "drainage-usage -safety production" and comprehensive gas control are well realized.

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