Mathematical analysis on influence of fan regulation in diagonal mine ventilation system

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Abstract
Air quantity regulation of fans has influence on the stability of mine ventilation system. To study the regulation of fans in joint operation and its influence in a diagonal ventilation system, mathematical method is adopted to analyze the influence law of air quantity regulating of fan in one of two wings on the air quantity, air pressure and resistance of itself and the fan in the other wing. The air quantity regulation of fan in one of two wings will affect the air quantity of fan in the other wing in a diagonal ventilation system, the influence results include airflow normal, airflow stagnation and airflow reverse in the other wing, and occurrence condition of influence results has been analyzed and discussed in this research. Air quantity regulation of fan in one of the two wings will increase the air pressure of itself and fan in the other wing.
Keywords: AIR QUANTITY REGULATION, INFLUENCE ANALYSIS, DIAGONAL VENTILATION SYSTEM, UNDERGROUND COAL MINE

1. Introduction

Mine ventilation system continuously transports fresh air into the underground coal mine for climate regulation, so as to provide a good working environment for workers and prevent the occurrence of disasters [1, 2]. The structural complexity of the ventilation system will directly affect the safety and reliability of the production system [3, 4]. Based on the distribution location of air intake and exhaust shaft in coal mine, the ventilation system can be divided into central, diagonal, regional type and mixed type [5]. The diagonal ventilation system has the advantages of large ventilation capacity, convenient air volume control, easy ventilation management and so on, and it is widely used in large underground mines in China [6]. The diagonal ventilation system, which contains a number of air routes and a plurality of places requiring airflow, is very complicated in the actual production of coal mine, as shown in Figure. 1.

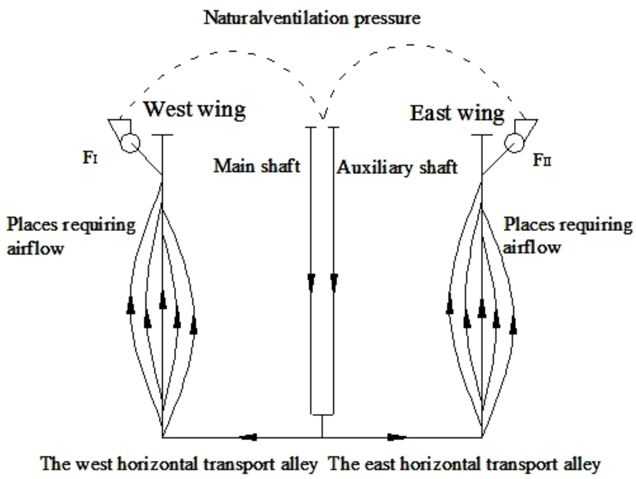

Figure 1. Complex diagonal ventilation system model

To facilitate the study of the problem, it is necessary to simplify the complex diagonal ventilation system. The simplification basis is the characteristics of the series and parallel connection network of the ventilation network [7, 8]. The main and auxiliary shafts are equivalently combined into an airway which is taken as common airway of airflow in coal mine. All parallel branches in east wing are equivalently combined into an airway, and all parallel branches in west wing are equivalently combined into another airway, thus obtained the simplification model diagonal ventilation system as shown in Figure. 2. The resistance of west-wing airway is R_1, and air quantity is Q_1. The resistance of east-wing airway is R_2, and air quantity is Q_2. The resistance of common airway is R_0, and total air quantity is Q_0. F_{II} represents east-wing fan, and F_I represents west-wing fan.

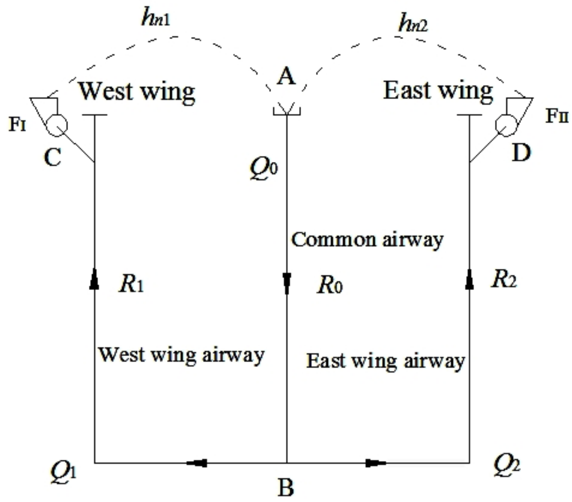

Figure 2. Simplification model diagonal ventilation system

The two fans are in a joint operation state in diagonal ventilation system, and each of them is not only related to each other but also influence each other [9-11], the reason for this is that air quantity in common air way is jointly produced by two fans. With the continuous development of production and exploitation of extension, air quantity regulating is needed due to the effects of geological conditions, safety factors and production layout and other factors [12]. Mine ventilation network satisfies Kirchhoff's law [13], and the change of air quantity in one branch which is connected with a node in the ventilation network leads to the change of air quantity in other branches at the same node [14, 15]. Air quantity regulating of fan in one wing will cause the change of ventilation parameters of itself and the fan in another wing. If the regulation is inappropriate, it may destroy the ventilation system of mine, which will affect the production and safety of mine seriously, therefore, it is necessary to study the regulation of fans' joint operation of and its influence in diagonal ventilation system.

The graphic method was mostly used in the previous study of the joint operation of multiple fans. This method has the disadvantages of complicated steps, large drawing amount and low precision, and the influence of natural ventilation pressure is not considered during the analysis process. This paper will adopt the mathematical method to analyze the influence law of air quantity regulating of fan in one of two wings on the air quantity, air pressure of itself and the fan in the other wing. It is assumed that the ventilation system has no air leakage in the process of research. The research results will provide guidance for the underground ventilation management, disaster prevention and equipment protection. It is assumed that the air flow of F_{II} is adjusted, the analysis is as follows.

2. Influence of air quantity regulation of F_{II} on air quantity of F_I

According to the research of the scholars, the influence of air quantity regulating of fan in one of two wings on the air quantity in the other wing and total air quantity in a simple diagonal ventilation system shown in Figure 2 is as follows [12]:

$$\begin{cases} \Delta Q_1 = -\dfrac{1}{1+K}\Delta Q_2 \\ \Delta Q_0 = \dfrac{K}{1+K}\Delta Q_2 \end{cases}, \quad K = \frac{R_1 Q_1 - \dfrac{a_1}{2} - a_2 Q_1}{R_0 Q_0} \tag{1}$$

where ΔQ_1 is change of air quantity in west wing caused by air quantity regulating in east wing, ΔQ_2 is regulation of air quantity in east wing, ΔQ_0 is change of total air quantity caused by air quantity regulating in east wing, a_1, a_2 are fitting equation parameters of the characteristic curve of west-wing fan. That ΔQ is positive means increase in Eq. (1), that ΔQ is negative means decrease in Eq. (1). R_1Q_1-a_1/2-$a_2Q_1 \geq 0$ exists according to the actual situation of coal mine production, thus the range of K is $[0,\infty)$ in Eq. (1).

It can be judged from Eq. (1) that increase of air quantity for east-wing fan will cause the decrease of air quantity for west-wing fan. Based on air quantity regulating of east-wing fan, the influence results are discussed according to the range of K.

(1) $K>0$

When $K>0$ exists in Eq. (1), $\Delta Q_0 < \Delta Q_2$ can be obtained, thus the increase of air quantity for east-wing fan leads to the increase of total air quantity, but it is unable to reach the expected increase effect of total air quantity.

1. Airflow stagnation in west wing

When west-wing airflow is stagnant, the air quantity in airway BC in Figure 2 is zero, thus the change of west-wing air quantity caused by regulation of east-wing air quantity is equal to -Q_1 (which means

ΔQ_1=-Q_1), and regulation of air quantity in east wing is $(K+1)Q_1$ at this moment according to Eq. (1), which means $\Delta Q_2=(K+1)Q_1$. Therefore, the occurrence condition of west-wing airflow stagnation is regulation of air quantity in east wing is $(K+1)Q_1$.

2. Airflow reverse in west wing

When west-wing airflow reverses, the west wing becomes intake of the east wing, thus the change of west-wing air quantity caused by regulation of east-wing air quantity is less than -Q_1 (which means $\Delta Q_1<-Q_1$), and regulation of air quantity in the east wing is greater than $(K+1)Q_1$ at this moment according to Eq. (1), which means $\Delta Q_2>(K+1)Q_1$. Therefore, the occurrence condition of west-wing airflow reverse is regulation of air quantity in the east wing is greater than $(K+1)Q_1$. It should be explained that, when the west-wing airflow reverses, the mine ventilation system will have two intake and one return duct,which will cause serious consequences and should be prohibited.

3. Airflow normal in west wing (Refering to the direction of airflow)

When west-wing airflow is normal, the change of west-wing air quantity caused by regulation of east-wing air quantity is great than -Q_1 (which means $\Delta Q_1>-Q_1$), and regulation of air quantity in east wing is less than $(K+1)Q_1$ at this moment according to Eq. (1), which means $\Delta Q_2<(K+1)Q_1$. Therefore, the occurrence condition of west-ing airflow normal is regulation of air quantity in the east wing is less than $(K+1)Q_1$. The smaller ΔQ_2 is, the smaller the change of west-wing air quantity is, and the ventilation system is also more stable.

(2) K=0

When K=0 exists in Eq. (1), $\Delta Q_1=-\Delta Q_2$ and $\Delta Q_0=0$ can be obtained, thus regulation of air quantity in the east wing has no influence on total air quantity but on west-wing air quantity, and the occurrence condition of different influence results is the same as that in K>0.

According to the above research, it is better to increase the value of K to prevent west-wing airflow stagnation and reverse caused by regulation of east-wing air quantity. It can be seen from Eq. (1) that the most effective measures of increase of K is to reduce resistance in common airway (R_0). The smaller the R_0 is, the more stable the ventilation system is.

3. Influence of air quantity regulation of F_{II} on pressure of itself and F_I

3.1. Change of air pressure for F_{II} after regulation

According to the law of resistance, $h_{BC}=R_1Q_1^2$, $h_{B\text{-}D}=R_2Q_2^2$ and $h_{AB}=R_0Q_0^2$ can be obtained in Figure 2.

Supposing the air pressure of east-wing fan (F_{II}) before regulation of air quantity is h_{II}, the air pressure balancing equation for circuit of A-B-D-A can be written in Eq. (2) according to Kirchhoff's second law.

$$h_{II} \pm h_{n2} = R_2 Q_2^2 + R_0 Q_0^2 \tag{2}$$

where h_{n2} is natural ventilation pressure for east wing, Pa. When natural ventilation pressure works with the ventilation system, "+" is adopted in Eq. (2). When natural ventilation pressure works against the ventilation system, "-" is adopted in Eq. (2).

Supposing the air pressure of east-wing fan after regulation of air quantity is h_{II}', the air pressure balancing equation for circuit of A-B-D-A can be written in Eq. (3) according to Kirchhoff's second law.

$$h_{II}' \pm h_{n2} = R_2(Q_2 + \Delta Q_2)^2 + R_0(Q_0 + \Delta Q_0)^2 \tag{3}$$

The change of air pressure of east-wing fan before and after regulation of air quantity is obtained as shown in Eq. (4) by subtracting Eq. (2) from Eq. (3).

$$\Delta h_{II} = h_{II}' - h_{II} = R_2(2Q_2\Delta Q_2 + \Delta Q_2^2) + R_0(2Q_0\Delta Q_0 + \Delta Q_0^2) \tag{4}$$

That Δh_{II} is positive means increase, and that Δh_{II} is negative means decrease in Eq. (4).

When east-wing air quantity increases by regulation ($\Delta Q_2>0$), $\Delta Q_0>0$ and $\Delta Q_1<0$ can be obtained according to Eq. (1), thus $\Delta h_{II}>0$ can be determined by Eq. (4). Therefore, the increase of the air quantity of main fan in one of the two wings by regulation will result in increase of the air pressure of itself in a diagonal ventilation.

3.2. Change of air pressure for F_I after regulation

Supposing the air pressure of west-wing fan (F_I) before regulation of east-wing air quantity is h_I, the air pressure balancing equation for circuit of C-B-D-C can be written in Eq. (5) according to Kirchhoff's second law.

$$(h_I \pm h_{n1}) - (h_{II} \pm h_{n2}) = R_1 Q_1^2 - R_2 Q_2^2 \tag{5}$$

where h_{n1} is natural ventilation pressure for east wing. When natural ventilation pressure works with the ventilation system, "+" is adopted in Eq. (5). When natural ventilation pressure works against the ventilation system, "-" is adopted in Eq. (5).

Supposing the air pressure of west-wing fan after regulation of east-wing air quantity is h_I', the air pressure balancing equation for circuit of C-B-D-C can be written in Eq. (6) according to Kirchhoff's second law.

$$(h_{\mathrm{I}}'\pm h_{n1})-(h_{\mathrm{II}}'\pm h_{n2})=R_1(Q_1+\Delta Q_1)^2-R_2(Q_2+\Delta Q_2)^2 \tag{6}$$

The change of air pressure of west-wing fan before and after regulation of east-wing air quantity is obtained as shown in Eq. (7) by subtracting Eq. (6) from Eq. (5).

$$h_{\mathrm{I}}'-h_{\mathrm{I}}=\Delta h_{\mathrm{I}}=\Delta h_{\mathrm{II}}+\{R_2[(Q_2+\Delta Q_2)^2-Q_2^2]\}+\{R_1[Q_1^2-(Q_1+\Delta Q_1)^2]\} \tag{7}$$

When east-wing air quantity increases by regulation ($\Delta Q_2>0$), $\Delta Q_0>0$, $\Delta Q_1<0$ and $\Delta h_{\mathrm{II}}>0$ can be obtained according to Eq. (1), thus $\Delta h_{\mathrm{I}}>0$ can be determined by Eq. (7). Therefore, the increase of the air quantity of main fan in one of the two wings by regulation will result in increase of the air pressure of main fan in the other wing in a diagonal ventilation.

3.3. Discussion

According to the above research, regulation of air quantity of main fan in east wing will cause the change of air pressure of main fan in west wing. The influence results is discussed as following from the perspective of air pressure of main fan. It is assumed that ventilation capacity of main fan in east wing is greater than that of main fan in west wing.

(1) Airflow stagnation in west wing

When west-wing airflow is stagnant, the air quantity in airway BC is zero (Q_1=0) in Figure 2 in this case. Q_0=Q_2 can be determined according to Kirchhoff's first law at node B. The air pressure balancing equation for ventilation circuit of C-B-A-C can be written in Eq. (8) according to Kirchhoff's second law.

$$h_{\mathrm{I}}\pm h_{n1}=R_0Q_0^2 \tag{8}$$

The air pressure balancing equation for ventilation circuit of A-B-D-A can be written in Eq. (9) according to Kirchhoff's second law.

$$h_{\mathrm{II}}\pm h_{n2}=R_2Q_2^2+R_0Q_0^2 \tag{9}$$

Eq. (9)/ Eq. (8) can obtain the following:

$$\frac{h_{\mathrm{II}}\pm h_{n2}}{h_{\mathrm{I}}\pm h_{n1}}=\frac{R_2Q_2^2+R_0Q_0^2}{R_0Q_0^2}=\frac{R_2}{R_0}+1 \tag{10}$$

Eq. (10) is the criterion for airflow stagnation in airway where fan with smaller ventilation capacity exists.

(2) Airflow reverse in west wing

The opposite direction airflow exists in airway BC, thus the direction of airflow is opposite to the given direction of airflow in ventilation network of Figure 2 in this case, which means Q_1<0. According to Kirchhoff's first law at node B, Q_0<Q_2 can be determined. Therefore, the following equation can be obtained:

$$h_{\mathrm{I}}\pm h_{n1}=R_1Q_1^2+R_0Q_0^2<R_0Q_0^2 \tag{11}$$

Eq. (9)/ Eq. (8) can obtains the following:

$$\frac{h_{\mathrm{II}}\pm h_{n2}}{h_{\mathrm{I}}\pm h_{n1}}>\frac{R_2Q_2^2+R_0Q_0^2}{R_0Q_0^2}=\frac{R_2}{R_0}+1 \tag{12}$$

Eq. (12) is the criterion for airflow reverse in airway where fan with smaller ventilation capacity exists.

(3) Airflow normal in west wing (Referring to the direction of airflow)

When west-wing airflow is normal, the direction of airflow is same as the given direction of airflow in ventilation network, which means Q_1>0. According to Kirchhoff's first law at node B, Q_0>Q_2 can be determined. Therefore, the following equation can be obtained:

$$h\pm h_{1}=R_1Q_1^2+R_0Q_0^2>R_0Q_0^2 \tag{13}$$

Eq. (9)/ Eq. (8) can obtains the following:

$$\frac{h_{\mathrm{II}}\pm h_{n2}}{h_{\mathrm{I}}\pm h_{n1}}<\frac{R_2Q_2^2+R_0Q_0^2}{R_0Q_0^2}=\frac{R_2}{R_0}+1 \tag{14}$$

Eq. (14) is the criterion for airflow normal in airway where fan with smaller ventilation capacity exists.

According to the above research, air pressure of main fans, natural ventilation pressure and resistance of ventilation network have influence on the stability of ventilation system. It should be stated that the occurrence conditions of the influence results discussed above are not contradictory to the section 2.2.

4. Conclusions

The air quantity regulation of one of two wings fan will affect the air quantity of the other wing in simple diagonal ventilation system, the influence results includes airflow normal, airflow stagnation and airflow reverse, and occurrence condition of influence results has been analyzed and discussed. One of the occurrence condition of airflow stagnation of the west wing after air quantity regulation of east-wing is that the regulation is equal to (K+1)Q_1, and the other one is that the ratio of ($h_{\mathrm{II}}\pm h_2$) to ($h_1\pm h_1$) is equal to ratio of R_2 to R_0 plus one. The two occurrence condition above are equivalent, and both of them can be taken as critical condition for the change of airflow direction in west wing. Air quantity regulation of fan in one of the two wings will increase the air pressure of itself and fan in the other wing. Although the study in this paper is based on the simplified diagonal ventilation system and ignores the air leakage, the research result still has important guiding significance to the production practice of the complex diagonal ventilation management.

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