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Airflow stabilization in airways induced by gas flows following an outburst

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ABSTRACT

This paper addresses airflow stabilization in airways induced by outburst gas flows after the disappearance of the outburst shockwave. Based on fluid dynamics theory, a mathematical model of an unsteady airflow in an airway was established. The formation conditions of additional force and gas ventilation pressure with their dynamic influences on airflow in an airway were investigated. The results of this study indicate that an additional force is created by the variation of the airflow rate after outbursts, and this force hinders changes to the airflow and maintains the airflow in its original state of motion. The gas ventilation pressure can be observed as an increase in the potential energy after coal and gas outbursts. For upward ventilation, the direction of gas ventilation pressure is positive and assists the ventilation. However, for downward ventilation, the direction of gas ventilation pressure is negative and hinders the ventilation. This hindrance may lead to an airflow reversal in the main airway.

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1. Introduction

Coal and gas outbursts are the most serious dynamic disasters during underground coal mining operations. Many studies have been conducted regarding these outbursts (Ruilin and Lowndes, 2010; Sobczyk, 2014; Wold et al., 2008; Xue et al., 2014). These studies can be placed into three main categories: (1) case studies and descriptions of outbursts. (2) theories and models of outbursts, and (3) the prediction and prevention of outbursts (Xue et al., 2011; Yang et al., 2012). However, because of the complexity of the outburst mechanism and other objective factors, coal and gas outbursts cannot be eliminated using current technology. After an outburst, the airflow stability can be disturbed by the outburst shock wave and gas flows, and the airflow stability can be divided into two stages. The first stage is the occurrence of an outburst. The high-energy shockwave induced by the outburst destroys the ventilation network structure instantly, changes the roadway resistance, and thereby has a significant impact on the airflow stability. The formation process of outburst shocks, the characteristics and patterns of the propagation, and the attenuation of the outburst shock waves have been modeled for coal and gas outbursts (Wang et al., 2012; Zhou et al., 2014, 2015). The second stage of the gas flow is the dynamic effect disappearance of the outburst shockwave. Methane in the airflow continues to flow and diffuse. The unsteady migration of this gas flow in the roadway produces “additional force” and “gas ventilation pressure”, and this gas flow also play important roles in the stability of the airway airflow. Many case studies show that airway airflow reversal can be induced by the shock wave, however, little attention has been paid to this gas flow stage. This paper studies the migration of the outburst gas flow in airways and analyzes its influence on the stability of the roadway airflow.

2. Influencing factors on the airflow stabilization in airways

In the field of control theory, stabilization refers to the ability of a system to return automatically to its original state of balance after it is subjected to a transient external disturbance causing the state to deviate from its original equilibrium state. The stabilization of a mine ventilation system generally refers to the stability of the airflow direction and airflow rate (i.e., the airflow direction remains unchanged, and the airflow rate changes do not exceed an allowable range).

Generally, in the running stage of mine ventilation, the ventilation status cannot be kept constant, as coal mine ventilation systems are relatively complicated (Haoran et al., 2015; Wallace et al., 2015; Zhu et al., 2012). Many influencing factors can control or impact the behavior of the system (Cheng and Yang, 2012). These

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factors include the ventilation network geometry (diagonal network, airway resistance, etc.), the operating characteristics of the main fans in the system (El-Nagdy, 2013; Kursunoglu and Onder, 2015), and the external disturbance factors, which include natural ventilation (Kazakov et al., 2015; Zapletal et al., 2014) and atmospheric pressure, etc. Many scholars have conducted extensive research concerning the ventilation network geometry and main fans. The airflow stabilization in airways induced by natural ventilation pressure and atmospheric pressure has also been clearly explained by researchers. The outburst gas flow is also an important external disturbance factor that influences the airflow stability by applying an additional force and gas ventilation pressure.

3. Mathematical model of the unsteady airflow in a single airway

A mining ventilation system is generally regarded to be steady when there are no disturbances. However, when the airflow mixes with an outburst gas flow, the airflow rate and velocity change, and the system is therefore unsteady. To analyze airflow stability caused by an outburst gas flow, a mathematical model of the unsteady airflow must be established.

To simplify this problem, the following is assumed that:

1. The air in the airway is incompressible.
2. The temperature change of the gas flow in the airway can be ignored.
3. The airway cross section remains unchanged.

Momentum equation of one-dimensional unsteady flow is described with the following equation (Dziurzynski et al., 2008):

$$\rho\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{\partial p}{\partial s} - \rho g\frac{\mathrm{d}z}{\mathrm{d}s} - w - j_D\delta(s - s_D) + h_f\delta\left(s - s_f\right) \tag{1}$$

where $\frac{du}{dt}$ is the acceleration of the airflow in the airway (m/s^2). s designates the spatial coordinate measured along the axis of the roadway (m). s_D is the coordinate of the point of occurrence of losses (m). S_f is the coordinate location of the fan (m). δ is the Dirac delta function. p is the absolute pressure (Pa). g is gravitational acceleration (m/s^2). ρ is the density of the airflow in the roadway (kg/m^3). z is the height coordinate, directed upwards (m). w is the viscous force per unit volume. j_D is the loss of pressure at the local resistance at coordinate s_D (Pa) and h_f is the pressure of the fan at coordinate s_f (Pa).

Integrating Eq. (1) along the length L of the airway results in the following equation:

$$\int_0^L \rho\frac{\mathrm{d}u}{\mathrm{d}t}\,\mathrm{d}s = -\int_0^L \frac{\partial p}{\partial s}\,\mathrm{d}s - \int_0^L \rho g\frac{\mathrm{d}z}{\mathrm{d}s}\,\mathrm{d}s - \int_0^L w - J_D + h_F \tag{2}$$

The pressure drop along the airway is

$$H = -\int_0^L \frac{\partial p}{\partial s}\,\mathrm{d}s \tag{3}$$

The pressure drop caused by the resistance of the airway is

$$\int_0^L w = Rq^2 \tag{4}$$

where R is the resistance of the airway, and q is the airflow rate. Given the acceleration $\frac{du}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s}$, if $u = u(t)$, then $\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{\partial u}{\partial t}$, $\sin\alpha = \frac{\mathrm{d}z}{\mathrm{d}s}$, and α is the dip of the airway. Therefore, Eq. (2) can be simplified as

$$H = \int \rho\frac{\partial u}{dt}\mathrm{d}s + \int \rho g\sin\alpha\mathrm{d}s + Rq^2 + J_D - h_F \tag{5}$$

Eq. (5) is the general differential equation of one-dimensional incompressible and unsteady flow, this equation can be utilized to analyze the unsteady flow in a single airway.

4. Role of the additional force on the stability of the airway airflow

4.1. Generation of the additional force

After coal and gas outbursts, the airflow state in the airway changes from steady to unsteady and the airflow rate of the airway varies with time. When an object moves under variable motion, its inertia can give the object a tendency to maintain its original state. If the object is taken as to be located at the coordinate origin, it behaves as if a force from the opposite direction acting on the object and this force is defined as additional force, the additional force is created from the variation of the airflow rate after outbursts. The additional force is a virtual force because it does not actually exist.

4.2. Expression and properties of the additional force

The additional force is determined by the mass and acceleration of the airflow. The acceleration of the airflow can be expressed as $\partial u/dt$ and the mass per cubic meter of the airflow is ρ. For a single airway, the additional force is $\int\rho\frac{\partial u}{dt}ds$, which is one term in Eq. (5).

The additional force generated by the variation of the airflow velocity after an outburst can be further expressed as

$$\int \rho\frac{\partial u}{dt}\,\mathrm{d}s = \rho L{*}\frac{\partial u}{dt} = \frac{\rho L}{A}{*}\frac{A\partial u}{\mathrm{d}t} = K\frac{\mathrm{d}q}{\mathrm{d}t} \tag{6}$$

where A is the cross section of the airway (m^2), $K = \frac{\rho L}{A}$ is the inertia coefficient.

By combining Eqs. (5) and (6), the additional force can be expressed as

$$K\frac{\mathrm{d}q}{\mathrm{d}t} = H - \int \rho g\sin\alpha\mathrm{d}s - Rq^2 - J_D + h_F \tag{7}$$

From Eq. (7), the following conclusions can be drawn.

When additional force is positive ($\mathrm{d}q/\mathrm{d}t > 0$), the direction of additional force is opposite to that of the main fan. In this case, if $q > 0$, the airflow flows with an accelerated motion, the airflow rate increases with time, and the additional force hinders its increase. If $q < 0$, airflow reverses and moves with a decelerated motion, the airflow rate decreases with time, and the additional force hinders its decrease.

When the additional force is negative ($\mathrm{d}q/\mathrm{d}t < 0$), the direction of the additional force is the same as that of the main fan. In this case, if $q > 0$, the airflow moves with a decelerated motion, the airflow rate decreases with time, and the additional force hinders its decrease. If $q < 0$, the airflow reverses and moves with an accelerated motion, the airflow rate increase with time, and the additional force hinders its increase.

In short, the direction of the additional force is always opposite to that of the changing trend of the airflow, the additional force hinders the change of the airflow and tends to keep the airflow in its original state of motion. From Eq. (6), the additional force is proportional to the change of the airflow rate and the airway length. The larger the initial airflow rate and the airway length are,

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