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The role of methane buoyancy on the stability of airway airflow in underground coal mine ventilation

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ABSTRACT

Coal mine ventilation is an extremely complicated system that can be disturbed by several factors. This paper addresses the fact that the stabilization of airflow in the airways can be induced by methane buoyancy. The formation and characteristics of methane buoyancy are further elaborated and combined with the airflow stagnation accident that occurred in the Tangshan coal mine in China. Field tests and experimental studies were conducted to verify the role of methane buoyancy on the stability of airway airflow. The results indicate that methane buoyancy is generated in inclined airways with gas accumulation, which can be regarded as an increment of buoyancy. Methane buoyancy can induce airflow stagnation or airflow reversals, especially in airways with relatively low airflow velocity. To maintain the stability of the airflow, in those airways with gas emissions, a higher airflow rate and velocity should be ensured, and large airways inclination should be voided.

1. Introduction

A ventilation system is an important component of an underground mining system. It should provide a sufficient quantity of air to underground mine operations (Chen et al., 2014; Jiang et al., 2015; Jin et al., 2016) to dilute methane and other contaminants (Kursunoglu and Onder, 2015; Wallace et al., 2015; Xu et al., 2016b), maintain a suitable working environment and prevent accidents from occurring. In the operational stage of mine ventilation, the status of the ventilation system simply cannot be kept constant. Generally, coal mine ventilation is an extremely complicated system. A large number of influencing factors can control or impact the behaviors of the system (Cheng and Yang, 2012; Xu et al., 2013; Kazakov et al., 2015). These factors include the ventilation network geometry (Diagonal Network, airway resistance, etc.), location and operating characteristics of other fans in the system (El-Nagdy, 2013) and other external disturbance factors. Buoyancy is an important form of external disturbance factors and has been observed since the beginning of underground mining. Buoyancy in underground construction projects can help optimize the design of their ventilation systems, reduce their energy consumption and avoid risking the accumulation of gases or toxic agents (Mazarrón et al., 2015). However, buoyancy can induce airflow reversal or reduce the airflow rate of certain airways in mine ventilation. Scholars worldwide have conducted extensive research in the field of buoyancy (Toraño et al., 2011; Hansen, 2015; Li et al., 2015; Sasmito et al., 2015). Buoyancy is produced by the difference in the air density between the intake and return airways. Previous studies have indicated that the difference in the air density is determined by the air temperature and airway elevation difference. Therefore, the buoyancy always occurs in airways with differences in the elevation and temperature. For instance, when a fire occurs in an underground mine, the smoke flows along the airway airflow direction, and the airflow temperature in the airway increases as the smoke spreads. Thus, the buoyancy is induced by fire if the airway has an elevation difference. However, apart from temperature differences, the buoyancy can be produced in an airway with an elevation difference due to the accumulation of gas, which is called methane buoyancy in this paper (Dziurzyn'ski et al., 2008; Wang et al., 2012; Wang et al., 2016; Zhou and Wang, 2016; Zhou and Wang, 2017). The methane buoyancy is often neglected by researchers and field staff. However, the methane buoyancy can lead to airflow stagnation or airflow reversal in normal airways. For instance, an accident involving the stagnation of airflow in an airway occurred in one inclined airway of the Tangshan coal mine in China. Initially, the accident was thought to be caused by the roof falling. However, after a detailed site investigation (Wang et al., 2014; Zhou, Wang et al. 2014, 2015; Xu et al., 2016a) was conducted, the results clarified that the accident was a result of gas accumulation.

This paper aims to explore the mechanism by which the stability of

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the airway airflow in underground mines is induced by methane buoyancy, present measures to prevent airway airflow disasters caused by methane buoyancy and propose recommendations for mine ventilation design.

2. Formation and characteristics of methane buoyancy

2.1. Factors that influence methane buoyancy

Methane buoyancy is caused by the accumulation of gas. It can be regarded as one form of buoyancy. The amount of methane buoyancy is primarily affected by the gas concentration and elevation difference in the airway. Because the density of methane is lower than that of air, the density of the mixed gas changes. Furthermore, when the airway has an elevation difference, the methane buoyancy is formed. The methane buoyancy can be calculated as Equation (1).

$$h_M = (\bar{\rho} - \rho_a)[z(0) - z(L)]g \tag{1}$$

where h_M is the methane buoyancy of the airway, Pa; $\bar{\rho}$ is the average density of the airway airflow after mixing with gas, kg/m^3; ρ_a is the density of air, kg/m^3; $z(0)$ and $z(L)$ are the node elevations of the beginning and end nodes of the airway along the airflow direction, m, respectively.

2.2. Characteristics of methane buoyancy

Based on Equation (1), the characteristics of the methane buoyancy can be summarized as follows:

1) The methane buoyancy is proportional to the elevation difference ($z(0) - z(L)$) of the airway; when the value of $z(0) - z(L)$ increases, the methane buoyancy increases. The methane buoyancy is also related to the gas concentration. The mixed gas has a lower air density as long as the methane is contained in the airflow, and for a higher gas concentration, the methane buoyancy is greater.
2) Methane buoyancy is similar to thermal drop of ventilation pressure which can change the airflow direction of an airway and thus induce disorder in the airflow in the mine. A different airflow direction in an inclined or vertical airway (upward ventilation or downward ventilation) plays a different role in the stability of the airflow of the airway.

2.2.1. Methane accumulating in an upward airflow

The density of methane is less than that of air under the same conditions; the density of the mixed gas can be expressed as $\rho = (\rho_m - \rho_a)c + \rho_a$ if methane appears in the airway. It is evident that $\rho - \rho_a < 0$, where ρ_m and ρ_a are the methane and air densities, respectively. The value c is the methane concentration. In the upward ventilation condition, $z(0) - z(L) < 0$. In this case, the direction of methane buoyancy generated in the airway is the same as that of the fan in the airway and thus adds impetus to the ventilation. Simultaneously, the airflow rate of the airway tends to increase whereas those of the other airways tend to decrease. When the methane buoyancy of the airway reaches a critical value, the airflow of other airways reverse, which cause methane to flow into the other airways along with the airflow.

2.2.2. Methane accumulating in a downward airflow

In the downward ventilation condition, $z(0) - z(L) > 0$, the direction of the methane buoyancy generated in the airway is opposite to that of the fan in the airway and hinders ventilation. Simultaneously, the airflow rate of the airway tends to decrease whereas those of the other airways tend to increase. When the methane buoyancy of the airway reaches a critical value, the airflow of the airway reverses, and methane may flow into other airways due to the reversed airflow.

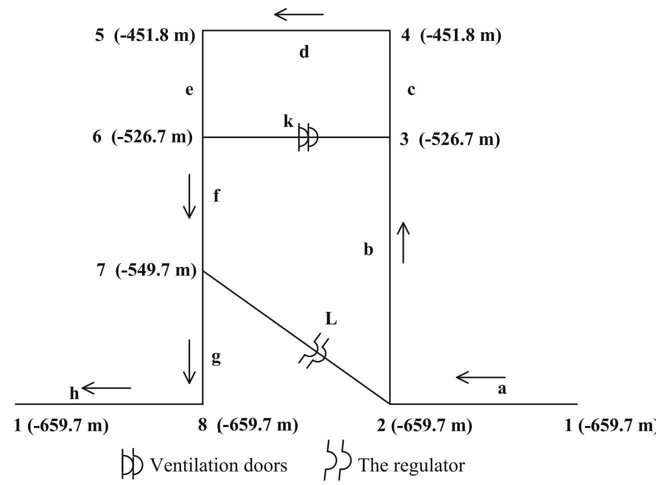

Fig. 1. Simplified ventilation system of the coal mine.

3. Case study on the airflow stability caused by methane buoyancy

3.1. Basic profile of the coal mine

As mentioned in section 1, the airflow stagnation in an airway occurred in one inclined airway of the Tangshan coal mine in China caused by methane buoyancy. The Tangshan coal mine is one of the oldest coal mines in China with 130 years of mining history. Production continues in the Yuexu area on the western border of the coal mine. The simplified ventilation system plane view is illustrated in Fig. 1, and parameters of the airways in the simplified ventilation system are listed in Table 1. Fig. 1 contains the node elevations. As shown in Fig. 1, airway c and airway e are two inclined airways, which are arranged in the coal seam. The inclinations of these two airways are both 30°, and they are connected by airways d and k. The two airways are full-pressure ventilation systems with an airflow rate of 6 m^3/s. Ventilation doors are installed in airway k.

3.2. The description of the accident

As shown in Fig. 1, the regulator in airway L was accidentally opened and produced a greater airflow rate from junction 2 to junction 7. There was no airflow in airway c, and the methane concentration above node 3 in airway c increased to more than 10%. Then, the regulator in airway L returned to normal operation. However, there still was no airflow rate in airway c. To investigate the reason for this phenomenon, the methane concentration was checked along airways b, c, e and f. The methane concentration exceeded 10% at points 20 m over junction 6 and 40 m over junction 3. No further checking above the areas was conducted because of safety considerations. The airflow stagnation was attributed to a floor fall in the local area of airway d, and gas accumulated in the airway that had no airflow. Based on this assumption, an auxiliary fan was placed in service to exhaust the accumulated gas. In approximately 24 h, the phenomenon of zero airflow rate suddenly disappeared, and the airflow rates in airways d and c returned to normal. The residual gas in the upper part was instantly discharged, but areas with a wide range of gas concentration exceeding the limits occurred along the airways.

In this accident, there were two abnormal behaviors. First, there was no airflow rate in airway c and airway d after the regulator in airway L returned to normal operation. However, exhausting for a period of time with an auxiliary fan produced a sudden discharge of gas, and the airflow returned to normal. Second, gas accumulated in airway c and airway d in a short period of time with extremely high gas concentrations. To explain these behaviors, field tests were conducted.