



Experimental study of high concentrations of coal mine methane behavior in downward ventilated tilted roadways



Kai Wang*, Zeqi Wu*, Aitao Zhou, Yifeng Jiang, Shuo Feng

Faculty of Resources & Safety Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China

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ABSTRACT

The movement and distribution of methane in coalmine roadways are major issues relating to coalmine safety. Once high concentrations of methane accumulate in downward ventilated tilted roadways, the movement of methane can be very special. A 1/50 experimental model was constructed for the study on high concentrations of methane behavior in downward ventilated parallel roadways. This experiment measured gas concentrations in the upper and lower parts of the methane accumulating roadway and the wind speeds both in the methane accumulating roadway and in its parallel roadway. The experimental results indicate that the methane draft pressure (the additional natural draft pressure due to the density difference of methane and air when high concentrations of methane accumulate in tilted roadways) could lead to airflow reversion in a downward ventilated roadway; methane may flow with the reversed airflow into the parallel roadway. The reversed methane that flows into the parallel roadway could generate a new methane draft pressure, which would oscillate airflow under certain conditions. According to the experimental results with parallel roadways of different windage, a larger windage of the parallel branch could ensure a relatively stable airflow, and a smooth methane discharge process. Through analysis by oscillation theory and the Archimedes number, it is concluded that the parallel roadway windage affects the methane draft pressure-caused airflow disorder by two aspects: (1) a larger windage decreases the amplitude of airflow oscillation and (2) a larger windage decreases the methane flow into the parallel branch, which, in turn, decreases the critical wind velocity for airflow reversion in the parallel roadway. The effect of windage is proved by a numerical simulation of Jiulishan Mine at the end of this paper.

1. Introduction

Methane can be found in most coal mines (Torano et al., 2009). A certain concentration of methane (approximately 5~15% in volume fraction) (Li et al., 2014; Shen et al., 2016; Takahashi et al., 1998; Zhang and Ng, 2015) in the roadway space has the potential to formulate an explosion (Deng et al., 2015). Thus, methane concentration control is one of the most important issues in the mining process (Wang et al., 2015).

Ventilation plays an essential role in diluting methane to a safe concentration (Gillies, 1983; Parra et al., 2006). In a coal mine ventilation system, air flows in a ventilation network that is constituted by roadways. The relationship of the volume flow and ventilation resistance in one roadway can be described by formula (1):

$$H = RQ^2 \quad (1)$$

where, H is the ventilation resistance of the roadway, in Pa; Q is the volume flow of the roadway, in m^3/s ; R is the windage of the roadway,

in $\text{N}\cdot\text{s}^2/\text{m}^8$. Windage is a concept usually used in mine ventilation; It depends on the friction factor, the cross area of the roadway, and the pressure drop through the ventilation facilities. Windage of a roadway without ventilation facilities can be calculated by formula (2):

$$R = \frac{\alpha UL}{S^3} \quad (2)$$

where, α is the friction factor, in $\text{N}\cdot\text{s}^2/\text{m}^4$; U is the circumference of the roadway, in m; L is the length of the roadway, in m; S is the cross section area of the roadway, in m^2 .

The movement and distribution of methane in a ventilated roadway has been a hot topic for researchers. Various numerical models, experimental systems and field measurement data were used in a methane behavior study in roadway space (Kurnia et al., 2014; Nakayama et al., 2002; Sasmito et al., 2013; Torano et al., 2009; Wala et al., 2003). However, most studies focused on low concentrations of methane in horizontal roadways. In these situations, the influence of methane on the ventilation can be quite small.

* Corresponding authors. Permanent address: Room 226, Zonghe Building, China University of Mining & Technology (Beijing), Beijing 100083, China.
E-mail addresses: kaiwang@cumtb.edu.cn (K. Wang), wzq371198354@126.com (Z. Wu).

However, methane concentrations can be quite high in some roadway spaces after abnormal cases such as a ventilation system malfunction or abnormal methane emission. Methane concentrations in some zones could even reach 100% (OTUONYE and Sheng, 1994). High concentrations of methane behavior in a roadway space can be quite different from the low concentrations. Wei Shanyang (Wei, 2013) and Cui Yongguo (Cui, 2014) studied migration of methane mass in a horizontal mining header. Wei and Cui proved that the attenuation law of the methane concentrations in the experiment met with a negative exponential function. Cui Yongguo also observed reversed flow in cross-roadways (the outburst shockwave leads to airflow reversion in one roadway, and methane flows in with the reversed airflow; subsequently, the methane flows back with the recovered airflow). Wei's experiments simulated methane outbursts with explosions of a small amount of gunpowder and simulated methane with nitrogen oxides produced by the explosion. The methane behavior in Wei's experiments was similar to the blasting gas behavior in other researchers' study (De Souza and Katsabanis, 1991; Torno et al., 2013). If the difference in shockwaves is ignored, the primary difference of the outburst and blasting is the different gases that are produced. The density of methane is lower than that of the blasting gases. When the concentration is high, the buoyancy of methane can affect the methane behavior quite a lot.

If high concentrations of methane accumulate in a tilted roadway, the methane movement pattern could be more complex. Zhou Aitao and his coworkers (Zhou et al., 2014a; Zhou et al., 2014b) innovatively extended the high concentrations of the methane migration study to parallel upward ventilated roadways, which are often found in actual situations. In the numerical simulation study of Zhou et al., the methane draft pressure (the additional natural draft pressure due to the density difference of methane and air when high concentrations of methane accumulate in tilted roadways) induces airflow reversion in the parallel roadway of the methane contained roadway. However, in upward ventilated roadways, methane draft pressure has the same direction with the ventilation pressure supplied by a fan in Zhou and his coworkers' study, and the influence of the methane draft pressure can be greater in downward ventilated roadways because of the different directions of the methane draft pressure and ventilation pressure.

For actual sites, methane accumulation in tilted roadways is sometimes found in coal mines. Methane accumulation could occur in areas such as newly unsealed alternate longwall working faces, tilted roadways with insufficient airflow and outburst methane intruded tilted roadways. When methane is discharged in these areas, unexpected methane movement could appear (He, 2005). Therefore, the study of high concentrations of methane behavior in downward ventilated tilted roadways is necessary. The work described here identifies and demonstrates the issues and fluid processes involved but is not a full and systematic study of the topic.

2. Experimental system

2.1. similarity parameters

To build an experimental system that closely mirrors the real situation, the geometric similarity, dynamic similarity, and kinematic similarity, must be well determined. These three types of similarities are relevant. If the geometric similarity ratio and the dynamic similarity ratio are determined, the kinematic similarity ratio can be determined accordingly. Geometric similarity requires the dimension of any part in the experimental system to be proportional to the corresponding dimension in the real situation. The geometric similarity ratio can be defined as below:

$$C_D = D_m/D_s$$

where, C_D is the geometric similarity ratio; D_m is the dimension of any

part in the experimental system, such as the length of a roadway in the experimental system; D_s is the corresponding dimension with D_m in the real situation.

The experimental system was designed to simulate a pair of 100 m-long parallel real roadways. The real roadways are 5 m diameter circular roadways supported with 25 cm wide, 16.5 cm thick, U-shaped steels. The bracket spacing of the U-shaped steels is 1.25 m. According to the space of the laboratory, the geometric similarity ratio C_D is determined to be 1:50 (Chow et al., 2010; Ko et al., 2010).

The dynamic similarity ratio requires any force in the experimental system to have the same direction and to be proportional to the corresponding force in the real situation. The dynamic similarity ratio can be defined as below:

$$C_F = F_m/F_s$$

where, C_F is the dynamic similarity ratio; F_m is any force in the experimental system; F_s is the corresponding force of the real situation.

The equivalent of the corresponding similarity criterions ensures dynamic similarity. However, experimental systems cannot always guarantee all of the forces in the experimental systems proportional to the corresponding forces of the real situation. Thus, the dominant forces are usually given priority in the determination of the dynamic similarity ratio (Zhang et al., 2014). In this experiment, the dominant force is the methane draft pressure which is essentially the gravity difference of the gas columns in the methane-containing roadway and its parallel roadway. Therefore, in determining the dynamic similarity ratio, the Froude number that characterizes the ratio of the gravity and inertia forces is given priority (Chow et al., 2010; Ko et al., 2010; Zhou et al., 2006). To achieve dynamic similarity, the Froude number of the experimental system and the real situation must be equal. The Froude number is defined by Formula (3):

$$Fr = V^2/gD \quad (3)$$

where, Fr is the Froude number; g is the acceleration of gravity, the changes of which is not considered in this experiment; D is the characteristic value of dimension; and V is the characteristic value of velocity.

Reynolds number similarity is also an important similarity in similar physical experiments. However, Reynolds similarity and Froude similarity cannot be achieved simultaneously. Because airflow in mine ventilation is almost maintained in a constant friction factor region, the Reynolds number similarity need not consider if the fluid in the experiment is also in the constant friction factor region. However, the constant friction factor region is difficult to reach continuously because, sometimes, the wind speed in the experiment is quite small. Therefore, we increased the roughness of the inner wall of the pipelines within a reasonable range to make the fluid as close to the constant friction factor region as possible.

From Formula (2), it can be deduced that to make the Froude numbers equal, the square of the characteristic velocity ratio should be equal to the geometric similarity ratio as shown in Formula (4):

$$V_m^2/gD_m = V_s^2/gD_s \Rightarrow V_m/V_s = \sqrt{D_m/D_s} \quad (4)$$

where, V_m is airflow velocity in any point of the experimental system; V_s is the corresponding velocity with V_m in the real situation.

Thus, the ratio of the characteristic value of the velocity should be $1:50^{0.5}$.

The kinematic similarity ratio requires the fluid velocity of any point in the experimental system to have the same direction and to be proportional to the corresponding velocity in the real situation. The kinematic similarity ratio can be defined as follows:

$$C_V = V_m/V_s$$

where, C_V is the kinematic similarity ratio.

Obviously, the kinematic similarity ratio of this experiment should be $1:50^{0.5}$. Therefore, the initial wind speeds in the experiments are

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