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Effect of concentration and obstacles on flame velocity and overpressure of methane-air mixture

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A B S T R A C T

Effect of concentration and obstacles on methane-air mixture deflagration to detonation transition (DDT) was investigated in a long circular duct with lengths of 40 m and inner diameter of 350 mm. Five different concentrations 6%, 8%, 10%, 12% and 14% (in this paper, concentration specifically refers to volume concentration unless otherwise specified) were selected for the various investigations. Experimental results show that flame reaches the maximum velocity when mixtures are near the stoichiometric concentration without obstacles while deflagration to detonation transition (DDT) may occur when obstacles are arranged in the duct. Four kinds of obstacles with blockage ratio of 0.3, 0.45, 0.6 and 0.75 are used in the experiment. The effect of obstacles on the flame velocity was investigate by inserting different number of obstacles (3, 6, 9 and 12) and adjusting spacing of obstacles (175 mm, 350 mm, 525 mm and 700 mm). The blockage ratio of obstacles as well as their spacing and number has great effects on the flame velocity of the mixtures. A high number of obstacles in the duct can increase flame turbulence and lead to flame acceleration. At a mixture volume concentration of 8%, flame propagates faster with an increase in obstacle spacing and DDT could happen. The larger the obstacle blockage ratio, the stronger the interaction of the unburned mixture with a shock wave, which is more beneficial to the acceleration of the flame, while more heat is dissipated with an increase of the obstacle blockage ratio and this is not good for flame acceleration and propagation, so final flame acceleration is determined by the two competing factors.

1. Introduction

The most common dust explosion occurs in underground coal mines. In coal mine tunnel, coal dust explosion is usually caused by gas explosion. Moving at the speed of sound, pressure wave resulting from gas explosion lifts the deposited coal dust in the air. Then gas flame reaches the coal dust causing a dust explosion which is more severe than the first one (Beidaghy Dizaji et al., 2014; Bidabadi et al., 2013, 2014, 2015; Soltaninejad et al., 2015). Methane-air mixture explosion is one of the most serious accidents in coal mines (Creedy and Phillips, 1997; Kissell, 2006; MSHA, 2009; Black and Aziz, 2009). When there is methane in coal mines, methane-air mixture may be ignited by the any strong ignition source and then generates a fierce chemical reaction. The accidental released methane often reacts in a certain concentration within the explosion limit which directly influences the reaction speed and the flame temperature. When methane-air mixture is ignited in a tunnel, the flame usually encounters a lot of obstacles during its propagation. These obstacles make the flame accelerate and could lead to great damage as a result of enormous pressure generated due to the methane-air mixture explosion. Under appropriate conditions, DDT can occur which might lead to very serious consequences. For this reason, the investigation of the effect of concentration and obstacles on methane-air mixture explosion and flame propagation is of important significance.

In terms of the effect of concentration on methane-air mixture explosion, Zipf, et al., 2013 undertook an experimental investigation in a duct with a diameter of 105 cm and the length of 73 m. Their results showed that detonations could be successfully initiated in methane-air mixture concentration between 5.3% and 15.5%. The measured detonation velocities were close to their corresponding theoretical Chapman-Jouguet (CJ) detonation velocity. Outside these detonation limits, failed detonations produced decaying detaching shocks and the flames propagated with

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velocities of approximately half of D_{CJ}. Dorofeev, 2002 gave different combustion mechanisms when the diameters of the ducts ranged from 174 mm to 520 mm under different methane concentrations. Ma et al., 2015 also conducted experiments in a tube with one end closed and the other open. They investigated the effect of concentration of methane-air mixture explosion. Due to the gas diffusion effect, mixtures with concentrations slightly higher than the stoichiometric concentration (11%) got the highest peak overpressure.

In terms of the effect of obstacles on methane-air mixture explosion, Lin et al., 1999 investigated the influence of obstacles on flame and explosion wave and found that obstacles intensify the turbulence phenomenon in the process of flame propagation. Yu et al., 2002 also found that, when an obstacle blockage ratis are the same, the final flame velocity has nothing to do with shape and spacing of obstacles, spacing of which only affects the rate of flame acceleration. Ciccarelli et al., 2005 experimentally studied the effect of circular obstacles on flame acceleration and found that the flame velocity reaches a maximum when the interval of obstacles is equal to the diameter of the tube under high blockage ratios. Johansen and Ciccarelli, 2009 investigated the effect of the obstacle blockage ratio on flame propagation. They found that the initial rates of flame acceleration were higher for large blockage ratios and can accelerate flame velocity close to the product of the speed of sound. Dong et al., 2012 also noticed that, the pressure rise rate increased locally when a single obstacle was mounted in a pipe, but it had little effect on the pressure and the mean maximum explosion overpressure increased with the increase of the obstacle's number. Na'inna et al., 2014 demonstrated that high congestion in a given layout does not necessarily imply higher explosion severity as traditionally assumed. Less congested but optimally separated obstructions can lead to higher overpressures. From the analysis of the above literature, it appears that the actual mechanism of the effect of concentration and obstacles on fuel-air deflagration to detonation transition (DDT) is lacking.

Hence, this present paper studies methane-air mixture explosion and flame propagation in the long and straight duct. Methane-air mixture explosion process under different concentrations without obstacles is analyzed in details. Furthermore, the effect of the number of obstacles (defined as n), their spacing (defined as S) and blockage ratio (the ratio of the obstacle area to cross-sectional area of the duct, defined as BR) on flame propagation is systematically investigated, which aimed at revealing the nature and mechanism of methane-air mixture explosion and flame propagation and providing the theoretical basis for preventing methane-air mixture explosion accidents in coal mines.

2. Experimental systems

Experiments were conducted in the horizontal explosion duct in the State Key Laboratory of Explosion Science and Technology. The experimental system was made up of the duct system, gas distribution system, ignition system, data acquisition system and high speed camera system. The duct was closed at both ends with its inner diameter of 350 mm and its total length of 40 m consisting of four long tubes and two short tubes. Test holes were evenly arranged every one meter on the long tubes, and ignition rod, transducers, vacuum gauge etc. were installed in the hole as presented in Fig. 1. The photograph of experimental equipment is shown in Fig. 2.

This experiment used an external trigger ignition system which included; ignition button, high speed camera system and data acquisition system. This was done to ensure personnel safety by avoiding triggering the system manually and keeping people away from the experimental site.

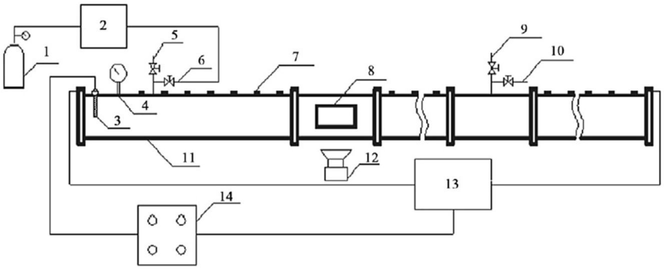

Fig. 1. Schematic diagram of gas explosion experimental duct (1-Gas, 2-Gas distributing device, 3-Ignition rod, 4-Vacuum gauge, 5-Air inlet, 6-Gas inlet, 7-Transducer, 8-Glass window, 9-Vacuum mouth, 10-Vent, 11-Experiment duct, 12-High speed camera, 13-Data acquisition system, 14- Trigger device).

Fig. 2. Experimental duct and obstacles.

Flame signals were displayed on the computer as they went through the transducers. Their propagation velocities could be measured as well. Fig. 3 shows the result of flame signals change over time at different positions. As soon as the methane-air mixture was ignited, the transducers captured the flame signals. Since the distance between the two adjacent flame signals was known, the average speed of the flame could be calculated by measuring the time between two adjacent transducers.

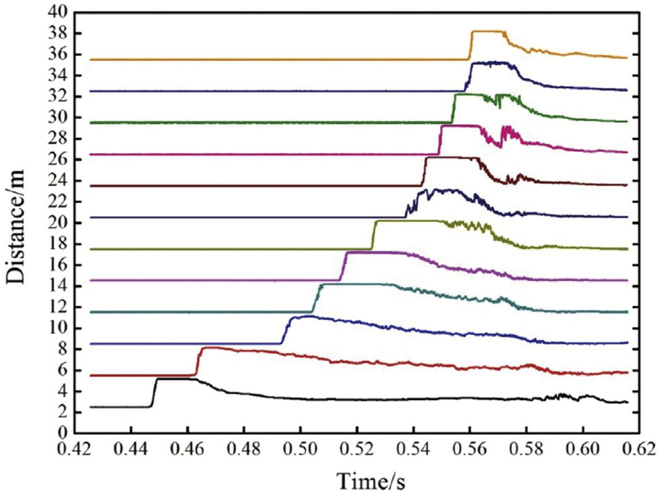

Fig. 3. Curves of flame signals change with time.