Journal of Loss Prevention in the Process Industries 34 (2015) 30–38

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Effects of premixed methane concentration on distribution of flame region and hazard effects in a tube and a tunnel gas explosion

Qiuju Ma, Qi Zhang*, Dong Li, Jiachen Chen, Shaoyun Ren, Shilei Shen

State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
13 January 2015
Accepted 14 January 2015
Available online 15 January 2015

Keywords:
Gas explosion
Methane concentration
Flame region
Shock wave
Experimental and numerical approach

ABSTRACT

Study of flame distribution laws and the hazard effects in a tunnel gas explosion accident is of great importance for safety issue. However, it has not yet been fully explored. The object of present work is mainly to study the effects of premixed gas concentration on the distribution law of the flame region and the hazard effects involving methane-air explosion in a tube and a tunnel based on experimental and numerical results. The experiments were conducted in a tube with one end closed and the other open. The tube was partially filled with premixed methane-air mixture with six different premixed methane concentrations. Major simulation works were performed in a full-scale tunnel with a length of 1000 m. The first 56 m of the tunnel were occupied by methane–air mixture. Results show that the flame region is always longer than the original gas region in any case. Concentration has significant effects on the flame region distribution and the explosion behaviors. In the tube, peak overpressures and maximum rates of overpressure rise $(dp/dt)_{max}$ for mixtures with lower and higher concentrations are great lower than that for mixtures close to stoichiometric concentration. Due to the gas diffusion effect, not the stoichiometric mixture but the mixture with a slightly higher concentration of 11% gets the highest peak overpressure and the shock wave speed along the tube. In the full-scale tunnel, for fuel lean and stoichiometric mixture, the maximum peak combustion rates is achieved before arriving at the boundary of the original methane accumulation region, while for fuel rich mixture, the maximum value appears beyond the region. It is also found that the flame region for the case of stoichiometric mixture is the shortest as 72 m since the higher explosion intensity shortens the gas diffusion time. The case for concentration of 13% can reach up to a longest value of 128 m for longer diffusion time and the abundant fuel. The "serious injury and death" zone caused by shock wave may reach up to 3–8 times of the length of the original methane occupied region, which is the widest damage region.

1. Introduction

Underground gas explosion often cause secondary disasters which are the main causes of mass death and casualty. High temperature flame generated in methane–air explosions are the main type of accident causing casualties in underground coal mines (Msiza, 2003). Moreover, coal dust explosions in a coal mine are usually caused by gas explosions, and such an accident can bring more severe disasters than single-phase gas explosion (Tan et al., 2011; Dong et al., 2012). Vent devices for gas and dust explosions are very common in process industry to discharge the combustion products or blast waves, the safety issue should draw much more attention. During the ducted or underground gas explosion, moving at the speed of sound, pressure wave resulting from gas explosion lifts the deposited coal dust or other combustible dust into the air. Then gas flame runs into the dust causing a dust explosion which is more severe than former gas explosion (Bidabadi et al., 2014; Ferrara et al., 2006). A great deal of investigation results of gas explosion accidents, together with many experimental study, show that the explosion and flame region is far longer than the initial premixed gas region, even reach more than several times of the length of original premixed gas region. The flame regions in methane-in-air explosions are more major hazards in underground coal mines. Therefore the determination of the flame region is significant for the gas explosion accident investigation.

Recent years, the problem has attracted researchers' attention. Xu et al. (2004) performed series of gas explosion experiments in a full-scale tunnel 886 m long and reported that the length of the

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* Corresponding author.
E-mail address: qzhang@bit.edu.cn (Q. Zhang).

http://dx.doi.org/10.1016/j.jlp.2015.01.018
0950-4230/

flame zone can be 3–6 times the length of the original gas accumulation zone. Pang et al. (2013) investigated the distribution laws of the flame region in tunnel gas explosion numerically.

Theoretically, during methane explosion (Bjerketvedt et al., 1997), explosion products expand and compress the medium ahead of the flame front surface, causing a compression wave. Owning to the chemical reaction, flame accelerates and the wave propagates faster and faster, meanwhile, the waves behind catch up with the foregoing one, and then the pressure, density and temperature rise sharply to form a detonation wave front which may propagate at a steady velocity as high as thousands of meters per second. This process is the formation of detonation. Due to the turbulence caused by the shock wave ahead of flame front, along with the promotion effect of the expanding gas products, the flammable gas accumulation area will extend a lot, and then the flame region exceeds the original gas occupied range as a consequence. Generally, gas explosions are mostly deflagrations but cannot achieve detonation or it can only achieve unstable detonation. This way, with regard to a certain length of initial methane accumulation region, various explosion levels will result in different flame regions.

For the given tube or tunnel inter structures, explosion intensity depends on volume fractions of methane in air. The quantitative relationship between the length of flame region and the length of the original premixed methane occupied region is greatly influenced by the explosion intensity degree. However, there has not yet been a definite conclusion about their relationship. In order to effectively prevent the loss from the explosion of methane/air mixture in mines, it is necessary to have some knowledge of the related explosion process and its action. Especially, effects of premixed methane concentration on distribution of flame region required further study.

The object of this study is to examine the effects of premixed gas concentration on the distribution laws of the flame region, the explosion characteristics and the hazard effects involving methane-air explosion in a tube and a tunnel based on numerical results and theoretical analysis.

The explosion overpressure time histories, and flame propagation can be obtained in the experiments. However, they are not enough to analyze the factors affecting flame region beyond the original premixed mixtures and its mechanism. Therefore, the numerical calculation was also used in this study.

2. Experimental apparatus and conditions

The experimental set-up used in this study consisted of a tube coupled with an electric ignition system, a data acquisition system. Experimental tests were conducted in a 10.9 m long tube with an internal diameter of 10 cm, with one end closed and the other end open, as shown in Fig. 1. The experimental apparatus consists of this explosion tube, an electric ignition system, a transient pressure measurement sub-system, a transient temperature measurement sub-system, a high speed photography sub-system and a data acquisition system. Explosions were monitored by means of Kistler pressure gauges and a fast-response temperature transducer mounted on the wall of the experimental vessel. All results were stored through a data acquisition device. In the experimental test, ignition point was located at the closed end of the tube, and the ignition was achieved by means of an inductive-capacitive spark produced between stainless steel electrodes with rounded tips, separated by a spark gap of 1 mm.

Tests were conducted with obstacles placed inside the first 1.5 m of the tube from the closed end. This obstacle zone includes several orifice plates with even spacing of 10 cm, and the area blockage ratio (BR), defined as the ratio of the cross-section area of the tube blocked by the obstacle and the tube cross-sectional area, is 0.36. The premixed methane region is fixed as 3.5 m long from the closed end. A 0.3-m long transparent tube is used, at 5.5 m from the closed end, so that a high-speed camera placed perpendicular to the tube can monitor the flame-spreading process. Eight pressure transducers are mounted to the tube along its axis.

All the experiments were conducted at atmospheric condition with six different premixed methane concentrations, 6%, 7%, 8%, 9.5%, 11% and 13%.

3. Numerical simulations

3.1. Solver

Numerical simulations were performed using a finite element computational code for fluid dynamics suitable for gas explosion and blast problems. The code solves Navier–Stokes partial differential equations numerically by means of the finite volume formulation (Patankar, 1980), because the integration of a partial differential equation over a finite control volume automatically ensures that during the computation conservation of mass, momentum, energy and any other transport of property for each control volume is automatically satisfied.

The momentum equation is

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{1}$$

where x_i is the space coordinate in the directions i, t is the time, ρ is the density, u is the flow velocity and p is the static pressure.

$$\tau_{ij} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\left(\rho k + \mu_t \frac{\partial u_i}{\partial x_j}\right) \tag{2}$$

Where the turbulent viscosity coefficient $\mu_t = C_\mu \rho k^2/\varepsilon$, k is turbulent kinetic energy, ε the dissipation rate of turbulent kinetic energy, C_μ a model constant ($C_\mu = 0.09$ m^2/s), andδ_{ij} is the Kronecker delta.

The conservation of mass equation is

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \tag{3}$$

The conservation of energy equation equals

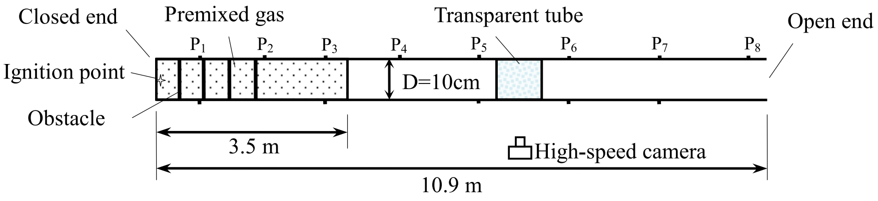

Fig. 1. Tunnel schematic view.