Contents lists available at ScienceDirect

Process Safety and Environmental Protection

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

Nonlinear distribution characteristics of flame regions from methane–air explosions in coal tunnels

Lei Pang[a,b,c,*], Tong Wang[c], Qi Zhang[b], Qiuju Ma[b], Lu Cheng[c]

[a] Beijing Institute of Petrochemical Technology, Beijing 102617, China
[b] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
[c] Beijing Municipal Institute of Labour Protection, Beijing 100054, China

ABSTRACT

High temperature flame fronts generated in methane–air explosions are one of the major hazards in underground coal mines. However, the distribution laws of the flame region in explosions of this type and the factors influencing such explosions have rarely been studied. In this work, the commercial software package AutoReaGas, a finite-volume computational code for fluid dynamics suitable for gas explosion and blast problems, was used to carry out numerical simulations of a series of methane–air explosion processes for various initial premixed methane–air regions and cross-sectional areas in full-scale coal tunnels. Based on the simulated results and related experiments, the mechanism of flame propagation beyond the initial premixed methane–air region and the main factors influencing the flame region were analyzed. The precursor shock wave and turbulence disturb the initial unburned methane–air mixture and the pure air in front of the flame. The pure air and unburned mixture subsequently move backward along the axial direction and mix partially. The enlargement of the region containing methane induces that the range of the methane–air flame greatly exceeds the initial premixed methane–air region. The flame speed beyond the initial region is nonzero but appreciably lower than that in the original premixed methane–air region. The length of the initial premixed methane–air region has substantial influence on the size of the flame region, with the latter increasing exponentially as the former increases. For realistic coal tunnels, the cross-sectional tunnel area is not an important influencing factor in the flame region. These conclusions provide a theoretical framework in which to analyze accident causes and effectively mitigate loss arising from the repetition of similar accidents.

Keywords: Gas explosion; Flame propagation; Tunnel; Shock wave; Temperature

1. Introduction

Methane–air explosions are one of the main types of accident causing casualties in underground mines. For a general ignition source, this type of explosion is usually manifest as a gas deflagration, in which a high temperature flame front is one of the major hazards. To effectively mitigate loss from accidents of this type in coal mines and provide a theoretical framework for the analysis of such accidents, a basic understanding of the relevant flame action is necessary.

Previous work on the flame action in methane–air explosions in coal tunnels and other similar gas explosions in tubes and tunnels has focused on the flame propagation speed and its influencing factors (Yu et al., 2002; Kobiera et al., 2007; Burluka et al., 2009; Domnina et al., 2009). These studies show that obstacles, especially multiple obstacles, play an important role in gas explosions (Tunik, 2000; Semenov et al., 2009). Based on a large body of experimental data on the deflagration of combustible gas in tubes, Silvestrini et al. (2008) argued that the wall roughness and presence of obstacles in the flame path act as turbulence generators, causing continuous flame acceleration.

In most studies related to flame action, long confined spaces were initially filled with a mixture of flammable gas and air. In the explosion processes generated by these initial conditions, the flame spread throughout the entire space, and the

* Corresponding author at: State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China. Tel.: +86 10 68914252; fax: +86 10 68914252.
E-mail address: panglei0525@163.com (L. Pang).
Received 18 May 2012; Received in revised form 29 September 2012; Accepted 5 October 2012
0957-5820/$ – see front matter
http://dx.doi.org/10.1016/j.psep.2012.10.016

spread range of the flame and its impact factors were usually neglected. However, in actual methane–air explosions in coal tunnels, the original premixed methane–air mixture occupies only a small portion of the tunnel. The methane–air flame rarely extends throughout the entire tunnel. Methane–air explosions in coal tunnels are a type of volume source explosions, in which the flame propagation is likely to be affected by precursor shock wave propagation, turbulence variations and other factors. There is a need for an in-depth investigation of the distribution laws of the flame region and their impact factors in this kind of accidental explosions.

In this paper, the commercial software package AutoReaGas, a finite-volume computational code for fluid dynamics suitable for gas explosion and blast problems, was used to carry out numerical simulations of a series of methane–air explosion processes in a full-scale coal tunnel. Based on the simulated results and related experimental analysis, the flame propagation mechanism beyond the initial premixed methane–air region was analyzed, and the relationship between the flame region and the initial premixed methane–air region was discussed.

2. Computational code

2.1. Numerical methods

As noted earlier, the commercial software package AutoReaGas, a finite-volume computational code for fluid dynamics suitable for gas explosion problems, was used to perform the numerical simulations. The gas explosion solver in AutoReaGas solves the conservation equations for mass, momentum and energy using the finite volume formulation. The turbulent flow field is described by the k-ε model. The combustion reaction is treated as a single-step conversion from reactants to products, and the volumetric combustion rate, R_c, in the mass conservation equation, is computed as in Salzano et al. (2002):

$$R_c = C_t \rho \frac{S_t^2}{\Gamma} R_{min} \quad (1)$$

where ρ is the mixture density, Γ is the turbulent diffusion coefficient for mass and/or energy, R_{min} is the minimum mass fraction among those of the fuel, oxygen and products and C_t is a dimensionless constant ($C_t = 100$; Salzano et al., 2002). The turbulent burning velocity, S_t, is expressed through the Bray correlation (Salzano et al., 2002):

$$S_t = 1.8 u_t^{0.412} L_t^{0.196} S_l^{0.784} \nu^{-0.196} \quad (2)$$

where u_t is the turbulence intensity, L_t is the turbulent length scale, S_l is the laminar burning velocity, and ν is the kinetic viscosity of the unburned mixture. The only physical mechanism of flame acceleration implemented in AutoReaGas is the burning rate enhancement owing to the flow turbulence generated ahead of the flame front. A quasi-laminar modification is used for the initial laminar combustion rate. The effects of pressure, temperature and flame front wrinkling on the laminar burning velocity are described by a dimensionless constant F_s ($F_s = 0.25$), which relates $S_{l,eff}$ to the flame radius, R_f, and theoretical laminar flame speed (Salzano et al., 2002):

$$S_{l,eff} = S_l(1 + F_s R_f) \quad (3)$$

AutoReaGas adopts the improved SIMPLE arithmetic to solve the coupling problem between pressure and velocity in an unsteady flow field. The computational domain is subdivided into a finite number of rectangular control volumes. The solution is evolved through time using a first order upwind time integration scheme. Stability of the solution algorithm is achieved by controlling the maximum time step used in the calculation, which is required to satisfy the standard Courant–Freidrich–Lewy stability criterion. AutoReaGas offers two different options for the handling of the computational grid. In the numerical simulation in this paper, the supports inside the tunnel or duct must be considered, and their scales are small compared with the section sizes of the tunnel or duct. The sub-grid option was therefore used in this work. Sub-grid objects were accounted for by a sub-grid representation. The basic idea of the sub-grid representation is that the objects are not represented by rigid boundary conditions in the flow field but rather by a set of cell properties that affect the flow in a manner representative of the presence of a sub-grid object or configuration of objects. The sub-grid details and limits on the validity of the AutoReaGas numerical predictions have been carefully assessed by Salzano et al. (2002), with good results for methane–air mixtures.

2.2. Experimental verifications

Generally, a full-scale experiment or small-scale experiment using a methane–air mixture is performed to verify the validity of the numerical method for a confined gas explosion. Numerical investigations of gas explosions in large scale tubes or full-scale tunnels using AutoReaGas have been performed as part of the NIOSH investigations of the Sago mine accident (Zipf et al., 2007). As a consequence of the Sago Mine accident in 2006, the US National Institute for Occupational Safety and Health (NIOSH; previously the US Bureau of Mines), began an initiative to evaluate the design of seals. One observation from the Sago accident was that the concrete seals applied were not nearly strong enough to withstand the explosion. In the research program initiated by NIOSH, one project included the simulation of existing NIOSH experiments (performed in the Lake Lynn experimental mine) to evaluate the ability of the simulations to predict or reproduce existing experiments. Thereafter, potential mine explosions on large scales were simulated to study the required seal strength as a function of the separation distance of the seals. Encouraging results were obtained; the average discrepancy between the calculated and measured explosion pressures in single-tunnel experiments was only approximately 13.6%. These results indicate that the blind predictive capability of AutoReaGas is quite good for scenarios involving gas clouds in tunnel systems.

A large scale experiment involving a gas explosion would be quite dangerous and costly. A long tube and an actual tunnel both belong to the category of confined spaces with large length-to-diameter (L/D) ratios. Therefore, in this paper, a small scale explosion experiment using a methane–air mixture was performed in a long tube to further verify the validity of the numerical method. The experimental tube is shown in Fig. 1. Five short steel tubes (T1–T5), one of length 0.4975 m

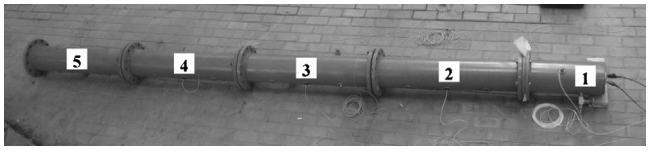

Fig. 1 – Experimental tube.