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Multiparameter acceleration characteristics of premixed methane/air explosion in a semi-confined pipe

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ABSTRACT

After a semi-confined pipe with a cross-section area of 0.08 × 0.08 m^2 and a length of 21 m, the multiparameter acceleration characteristics of a methane/air mixture with a fuel concentration of 9.5% and a filling ratio of 100% were simulated. The results show that a shock wave and a sonic compression wave produce two peak overpressures after 4.16 m away from the ignition source. The maximum overpressure presents a changing trend of decreasing and increasing with increasing distance. With increasing distance from the ignition source, the peak overpressure formed by shock wave, the flame propagation speed, the maximum combustion rate, the maximum density, and the maximum gas velocity increased gradually, but the peak overpressure formed by sonic compression wave and the maximum temperature decreased gradually. This will provide a basis of gas explosion control research.

1. Introduction

Gas or dust explosion is one of the main disasters threatening safety in the coal mining, gas transportation, and other related fields (Ding et al., 2017; Lolon et al., 2017; Lu et al., 2017). In coal mine roadway, dust explosion is usually caused by gas explosion. Sonic compression wave of gas explosion lifts the deposited coal dust in the air. Then gas explosion flame reaches the coal dust causing a dust explosion which is more severe than the first one (Bidabadi et al., 2013, 2014, 2015; Dizaji et al., 2014; Soltaninejad et al., 2015). In order to prevent losses, there is still a need for studying the gas explosion propagation.

Flame acceleration and transition to detonation was first comprehensively reviewed by Lee et al. (1969) and more recently by Ciccarelli and Dorofeev (2008), a more recent review, especially of insights into the final transition to detonation processes gained from numerical simulation was due to Oran et al. (2007). A considerably large amount of experimental data on the deflagration-to-detonation transition (DDT) and its run-up distance (the distance between the ignition point and the location of onset of detonation) were accumulated (Blanchard et al., 2011; Chan and Dewit, 1996; Grune et al., 2013; Silvestrini et al., 2008; Thomas et al., 2010; Yageta et al., 2011). The basic mechanism of Flame Acceleration (FA), the results of recent studies on FA, and their application to explosion safety were summarized by Dorofeev (2011). A review on the genesis and flame acceleration of methane-air explosions was reported by Kundu et al. (2016). The influence of initial temperature of a hydrogen-air mixture on deflagration-to-detonation transition (DDT) in a 27-cm-inner diameter, 21.3-meter-long heated detonation tube with several periodic orifice plates being equipped was experimentally investigated by Ciccarelli et al. (1996). The flame propagation of premixed liquefied petroleum gas (LPG) explosion was reported by Huo and Chow, 2017 The effects of hollow-square obstacles on gas explosion flame propagation were studied by Yu et al. (2016). The influence of obstacle separation distance on the flame acceleration was investigated by Náinna et al. (2015). Explosions in pipes with a bend were studied using experiments and numerical simulations (Blanchard et al., 2010; Kosinski, 2007; Phylaktou et al., 1993; Zhou et al., 2006). The flame acceleration in pipes containing bends of three angles (90°, obtuse angle and acute angle) was revealed by Zhu et al. (2016). An interesting study about shockwaves and

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detonation propagation through U-bend tubes was carried out by Frolov et al. (2007a, 2007b). Propane-air explosions were also carried out in coiled pipes and pipes with multiple U-shaped bends (Frolov, 2008). The flame propagation in pipes containing three different types of bifurcation was studied by Lin et al. (2016). The effect of experimental scale on the degree of similarity with real-world incidents was demonstrated for a methane-air explosion and its shock wave in a gallery based on numerical simulations (Zhang et al., 2011).

Despite many publications on gas explosions, few studies have been devoted to the multiparameter acceleration characteristics of premixed methane/air explosion in a semi-confined pipe. The multiparameter temporal and spatial evolution characteristics of gas explosions were simulated to provide a basis of gas explosion control research.

2. Numerical method and model

2.1. Numerical method

Numerical simulation was performed with AutoReaGas 3D computational fluid dynamics software developed by the Century Dynamics Company of America and the TNO of Netherlands. The software was primarily used to simulate flammable gas explosions and the subsequent blast effects (Jiang et al., 2016a). The explosion types modeled by AutoReaGas primarily comprised deflagrations rather than detonations. The reliability of the AutoReaGas software has been verified in numerous reports. For example, in the famous BFETS test, a fair correlation was observed between results from the simulation and experimental data. A comparison with available experimental data revealed that computational results obtained using the AutoReaGas software were satisfactory for relatively slower turbulent deflagration protocols (Salzano et al., 2002). The AutoReaGas code has been calibrated based on experimental results, and it was possible to generate relatively accurate simulations of similar geometries and to calculate the pressure loading of the structure at any spot within the space simulated (Janovsky et al., 2006).

2.2. Verification of numerical method

To validate the numerical results with experimental data, an experimental apparatus was constructed (as shown in Fig. 1), and numerical calculations simulating the experimental conditions were conducted.

The length of the experimental pipe was 5.0 m with a cross-section of 0.08 × 0.08 m^2, and the two ends of the pipe were closed (as shown in Fig. 2). The volumetric concentration of methane in the methane/air mixture was approximately 10%. Nine pressure sensors were placed along the pipe at 0.5 m intervals. Ignition was actuated at a closed end with a 2-J combustion engine spark plug. According to the experimental conditions, the methane/air explosion and its blast process were simulated using AutoReaGas.

Fig. 2. Pipes for numerical model calibration.

The numerical simulation was carried out using two different grid sizes to verify the results' sensitivity to changes therein. One was based on a 2 cm × 2 cm × 2 cm cubic cell; the other on a 4 cm × 4 cm × 4 cm version. Therefore, the number of cells was 16,000 and 2000, respectively. The relative discrepancy of the two different grid cell sizes at various distances is shown in Table 1. As can be seen from Table 1, the 2 cm × 2 cm × 2 cm grid was more accurate. The relative error between the calculated and the experimental results may have resulted from both the experimental limitations and the numerical simulation. Therefore, the 2 cm × 2 cm × 2 cm cube cell grid was adopted for further numerical simulations. The numerical model was compared with the experimental results as displayed in Fig. 3. The relative error between calculated and experimental peak overpressures is presented in Table 2. The numerical simulation agreed closely with the experimental results. The maximum relative error between numerical and experimental results was 8.44%. The experimental pressure of methane/air explosion had some internal error due to the precision and sensitivity of the pressure sensors. Therefore, the relative error between the calculated and experimental results may arise from both experimental limitations and the numerical simulation.

2.3. Numerical model and conditions

A semi-confined pipe model of 21 m in length and with a cross-

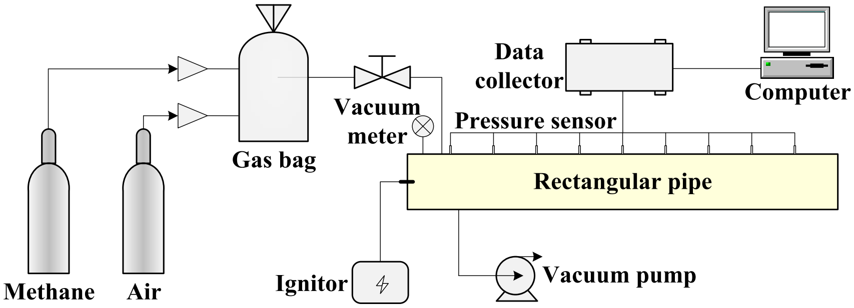

Fig. 1. Layout of pipe system for numerical model calibration.