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Effects of changes in fuel volume on the explosion-proof distance and the multiparameter attenuation characteristics of methane-air explosions in a semi-confined pipe

Bingyou Jiang [a, b, *], Mingqing Su [a], Zegong Liu [a, b, **], Feng Cai [a, b], Shujie Yuan [a, b], Shulei Shi [c], Baiquan Lin [d]

[a] Key Laboratory of Safety and High-efficiency Coal Mining, Ministry of Education, Anhui University of Science & Technology, Huainan, Anhui 232001, China
[b] School of Mining and Safety Engineering, Anhui University of Science & Technology, Huainan, Anhui 232001, China
[c] School of Economics and Management, Anhui University of Science & Technology, Huainan, Anhui 232001, China
[d] School of Safety Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China

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ABSTRACT

After establishing a semi-confined pipe model with a length of 100 m and a cross-sectional area of 0.08 m × 0.08 m, the multiparameter attenuation characteristics of gas explosions were revealed for fuel volumes of 0.0128 m^3, 0.0384 m^3, 0.064 m^3, and 0.0896 m^3. The results showed that the maximum overpressure presented a changing trend of decreasing, increasing and decreasing with increasing distance away from the ignition source. The peak overpressure formed by the shock wave, the flame propagation speed, the maximum density, gas velocity, and combustion rate all followed a trend of increasing and decreasing. However, the peak overpressure formed by the sonic compression wave and the maximum temperature decreased gradually as the distance increased. The fuel volume had a distinct effect on the overpressure, density, temperature, gas velocity, and combustion rate of gas explosions. The maximum overpressure, density, temperature, gas velocity, and combustion rate among all of the gauge points increased as the fuel volume increased, and they were almost all linear functions of the fuel volume. The explosion-proof safety distance tended to increase with increasing fuel volume, while the flameproof distance increased linearly. These results can provide theoretical guidance for the disaster relief efforts of the gas explosion in the process industry.

1. Introduction

In spite of much technological development and improvement of safety management, gas explosions in the process industry are still common safety accidents leading to casualties and huge financial losses. The risk of gas explosion widely exists in the mining, transportation and utilization processes related to the flammable gas (Si and Yuan, 2011; Qu and Lin, 2013). In order to prevent losses, there is still a need for exploring the propagation laws of the gas explosion.

After a gas explosion occurs in a pipe (or a tunnel), a shock wave propagates and decays due to the consumption of flammable gas and some irreversible energy losses such as the heat conduction and the thermal radiation within the wave front, and attenuates to a sound wave in the end (Wang and Xie, 1989). Thus, there will be a safety distance which is the minimum distance from the explosion source to the location necessary to avoid the harms of the shock wave to personnel (Wang and Xie, 1989). The safety distance can be calculated as the distance from the explosion source to the location where the shock wave attenuates to the sound wave. Research on the multiparameter attenuation characteristics and the safety distance of a gas explosion may have great significance on the disaster relief efforts and the treatment of the gas explosion.

The flame acceleration mechanism and the process by which a shock wave transforms into a detonation have been widely researched (Chan and Dewit, 1996; Oran and Gamezo, 2007; Silvestrini et al., 2008; Thomas et al., 2010; Blanchard et al., 2011; Dorofeev, 2011; Grune et al., 2013). The attenuation

* Corresponding author. School of Mining and Safety Engineering, Anhui University of Science & Technology, Huainan, Anhui 232001, China.
** Corresponding author. School of Mining and Safety Engineering, Anhui University of Science & Technology, Huainan, Anhui 232001, China.
E-mail addresses: cumtjiangby@163.com (B. Jiang), zegongliu@126.com (Z. Liu).

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characteristics of a shock wave traveling through various materials have been studied. Studied materials include polyurethane foam, granular materials, and filter (Britan et al., 2001; Nakazawa et al., 2002; Golub et al., 2005; Kitagawa et al., 2005, 2006, 2009; Rochette, 2007). Experimental investigations of shock waves attenuated through air were carried out in rough pipes (Gel'fand et al., 1990). A large number of theoretical and experimental relations had been proposed to describe the dependences of blast-wave intensity with distance from the center of an explosion (Borovikov and Vanyagin, 1976; Vovk et al., 1984; Rodionov et al., 1991; Mikhalyuk and Zakharov, 2001). Wang (2009) carried out some explosion experiments in a large diameter pipe filled with methane-air mixtures, and obtained that the maximum pressure of shock wave firstly decreased near the explosion source, and rose to certain maximum value and then gradually attenuated.

Obviously, the previously published works mentioned above pay more attention to the shock wave attenuation. Although the study of explosion distance is widespread in many fields, such as engineering blasting, liquefied natural gas explosion and fire prevention (Wang, 1982; Feng, 2007; Xia et al., 2012), little research is focused on the explosion-proof safety distance of premixed methane/air explosions in the process industry. Furthermore, the effect of fuel volume on the explosion-proof distance of gas explosions is studied even less. Jiang et al. (2012) emphasized the effects of the initial temperature and the initial pressure on the explosion-proof distance and calculated the explosion-proof distance of gas explosions using numerical simulation. Utilizing a numerical analysis tool, AutoReaGas, the effect of fuel volume on the explosion-proof distance of gas explosions was simulated to provide theoretical guidance for the disaster relief efforts of the gas explosion in the process industry.

2. Numerical method and model

2.1. Numerical method

Numerical simulation was performed with a 3D computational fluid dynamics software called AutoReaGas. The software was mainly used to simulate flammable gas explosions and the subsequent blast process. The reliability of the AutoReaGas software had been verified. For example, in the famous BFETS test, the simulation results agreed closely with the experimental data. The computational results acquired with the AutoReaGas software were satisfactory for the relatively slow, turbulent deflagration regimes when compared with the available experimental data (Salzano et al., 2002). Using the experimental results, the AutoReaGas code was calibrated, enabling the construction of accurate simulations in similar geometries and the calculation of the pressure load on the structure at any point in the simulated space (Janovsky et al., 2006).

2.2. Validation of the numerical method

In order to validate the numerical results with experimental data, an experimental apparatus was constructed, and numerical calculations simulating the experimental conditions were conducted.

The cross-sectional area of the experimental pipe was 0.08 m × 0.08 m with a length of 5.0 m. The premixed methane/air mixture with a fuel concentration of 10% was used to fill the pipe. Ignition was actuated at a closed end with a 2-J combustion engine spark plug. The methane/air explosion and its blast process were simulated using AutoReaGas according to the experimental conditions.

Numerical simulations were performed using two different grid sizes to verify the sensitivity of the results. One grid size was based on a 2 cm × 2 cm × 2 cm cubic cell, and the other was based on a 4 cm × 4 cm × 4 cm version. The relative error between the two different grid cell sizes was showed in Table 1. The 2 cm × 2 cm × 2 cm cube cell grid was observed to be more accurate. Therefore, the 2 cm × 2 cm × 2 cm cube cell grid was used for further numerical simulations. Fig. 1 showed the comparison between the AutoReaGas software model and experimental results. The relative error between the calculated and experimental maximum overpressures was presented in Table 2. The maximum relative error was 8.44%. The numerical simulation results agreed closely with the experimental ones.

2.3. Numerical model and initial conditions

A computational domain of 100 m × 0.08 m × 0.08 m along *x*, *y*, and *z* axes was specified by AutoReaGas software to simulate an unobstructed pipe with a length of 100 m and a cross-sectional area of 0.08 m × 0.08 m, as shown in Fig. 2. The terminal wall of this pipe was open, and the other walls were closed with the boundaries being all adiabatic and frictionless. The explosion gas was a mixture of methane and air with 9.5% fuel concentration, and it had a uniform distribution within the range of 2 m, 6 m, 10 m and 14 m in the front of the pipe where the fuel volumes were 0.0128 m^3, 0.0384 m^3, 0.064 m^3 and 0.0896 m^3, respectively. In the simulations, the initial temperature was set to 288 K by default, and the initial pressure was set to 101.3 kPa. Arranging 99 gauge points with the separation distance of 1 m from the ignition location along the cross-section center of the pipe, the overpressure, density, temperature, gas velocity, and combustion rate in the gas explosion were monitored. There were 1000, 4, and 4 grids along the *x*, *y*, and *z* directions yielding 16,000 grids and 25,025 nodes in total. (The grid size is small enough under the condition where the grid number is not more than the limit of AutoReaGas software.) The ignition source was located at the center of the cross-section at the pipe's closed end, and the radius of the initial spherical flame was 1.35×10^{-2} m by default. The maximum computational cycle was set to 20,000, and the termination time was 20 s. The governing equations and the k-ε turbulence model of gas explosions have been detailed by Jiang et al. (2012). Hence, this paper focuses on the effect of fuel volume on gas explosion propagation and the explosion-proof distance.

3. Results and discussion

Fig. 3 showed the profiles of the maximum overpressure versus distance from the ignition source for various fuel volumes. The maximum overpressure followed a changing trend of decreasing, increasing and decreasing with increasing distance. After the gas explosion occurred, the explosion products compressed the unburned gas and formed many compression waves. The closed-end overpressure near the ignition source decreased and reduced to zero. Many rarefaction waves were formed near the closed end. Due to the rarefaction waves, the peak overpressure formed by the compression wave decreased gradually. At this time, the peak overpressure formed by the shock wave was lower than that

Table 1
Relative error between two different grid cell sizes.

Distance (m)	Experimental results (MPa)	Numerical results (MPa) and relative error			
		2 cm × 2 cm × 2 cm		4 cm × 4 cm × 4 cm	
0.5	1.0809	1.12317	3.91%	1.01	−6.56%
2.5	0.99738	0.92947	−6.81%	0.88	−11.77%
4.5	1.1128	1.14154	2.58%	1.04	−6.54%