Fuel xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fuel

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

Effects of gas concentration and venting pressure on overpressure transients during vented explosion of methane–air mixtures

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HIGHLIGHTS

- Four major overpressure transients were identified during explosion.
- Four typical ΔP–t profiles with different overpressure transients were detected.
- Occurrence & characteristics of peaks depended on concentration & venting pressure.
- Overpressure in chamber was nearly uniform during explosion.

ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form 14 January 2016
Accepted 28 January 2016
Available online xxxx

Keywords:
Methane–air mixtures
Vented explosion
Peak overpressure
Rate of overpressure rise
Methane concentration
Venting pressure

ABSTRACT

29 batches of vented explosion tests were conducted in a 12 m^3 concrete chamber filled with methane–air mixtures to investigate the effects of methane concentration and venting pressure on the development of overpressure inside the chamber. The deflagrations were vented from a square side window with a venting area of 0.64 m^2 upon rupture of the vent cover. The venting pressures were varied by using six different types of vent covers, and determined by performing a numerical simulation. Methane concentrations in the mixed gas varied between 6.5 and 13.5 vol.%, covering both lean and rich combustion regimes. The generation conditions of the four types of overpressure–time profiles with different overpressure transients were summarized. Among the overpressure transients, the ΔP_1 caused by failure of the vent cover and the ΔP_4 resulted from the coupling between acoustic mode and flame were basically dominant. The rate of ΔP_1 rise as well as peak value of ΔP_1 and ΔP_4 showed a same trend of first increasing and then decreasing with the methane concentration from lean to rich. They reached their maximum value at the methane concentration of about 9.5%, whereas the rate of ΔP_4 rise was found to be insensitive to the methane concentration. The peak value of ΔP_1 increased with the venting pressure, while that of ΔP_4 first increased and then decreased as the venting pressure increased. In addition, the rates of ΔP_1 and ΔP_4 rise were both insensitive to the venting pressure. The occurrence of ΔP_4 was depended on the methane concentration and the venting pressure. The differences in the behavior of these overpressure transients suggest their different generation mechanisms.

1. Introduction

Natural gas is a clean-burning hydrocarbon fuel with high calorific value and low carbon footprint compared to other fossil fuels, such as coal [1]. However, due to the frequent gas explosion accidents in recent years, more and more attention has been paid to the severity of natural gas explosion [2]. When an explosion occurs in an enclosed space, it imposes significant danger to occupants and tremendous damage to the buildings in the vicinity. The damage level of a gas explosion is mainly dependent upon the magnitude of the overpressure transients and the loading duration. The gas concentration and the venting pressure play key roles in the evolution of overpressure [3]. Hence, to reduce the loss of accidents, it is essential to study the effects of gas concentration and venting pressure on the overpressure transients during the vented gas explosion.

Different types and numbers of overpressure transients have been reported in the literatures [4–9] from vented gas explosion tests.

Cooper et al. [4] conducted vented explosion tests in five near-cubic enclosures with natural gas–air, propane–air and ethylene–air mixtures, employing low-failure-pressure explosion relief panels. A typical overpressure–time profile with four major overpres-

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http://dx.doi.org/10.1016/j.fuel.2016.01.084
0016-2361/© 2016 Published by Elsevier Ltd.

sure transients were reported, as shown in Fig. 1. It was found that ΔP_1 was a constant value higher than the venting pressure when the venting pressure was greater than 3 kPa. ΔP_4 reached maximum on a slightly fuel-rich mixture and slightly increased with the venting pressure from 0 to 26 kPa. Guo et al. [5] performed vented hydrogen–air explosion tests in a cylindrical vessel with a neck. Four overpressure transients were also observed, however, the generation mechanism of ΔP_2 and ΔP_4 were different with those reported by Cooper et al. [4], as shown in Table 1. In these tests, as the venting pressure increased, ΔP_1 became the dominant peak, while ΔP_2 and ΔP_3 gradually vanished. Another overpressure–time profile with six overpressure transients was detected by Fakandu et al. [6]. They conducted the tests in a 10 L cylindrical vented vessel with 10 vol.% methane–air and 7.5 vol.% ethylene–air mixtures, and found that P_{burst} was the controlling overpressure transient for vent area of 0.013 m^2 and 0.026 m^2. Chen et al. [7] investigated the explosion venting of methane–air mixtures in a cylindrical vessel with a diameter of 180 mm and length of 300 mm. They observed that two overpressure transients, ΔP_1 and ΔP_2, appeared during the explosion; ΔP_2 increased with the rise of the venting pressure. Chow et al. [8] conducted vented explosion tests in a 3:1 aspect ratio cylindrical vessel with methane–air, propane–air and ethylene–air mixture. The explosion gave rise to three overpressure transients, and the increasing of the vent failure pressure generally resulted in that ΔP_1 became the main feature of the observed overpressure–time profile. In another group of vented hydrogen–air explosion tests in a 63.7 m^3 rectangular chamber, three overpressure transients were reported by Bauwens et al. [9], it was found that P_{vib} decreased by reducing hydrogen concentrations from 19 to 12 vol.% within the lean combustion regime.

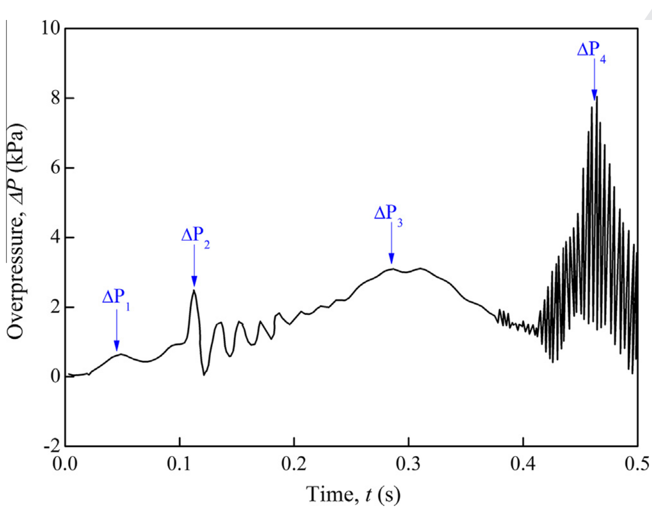

Fig. 1. Typical overpressure–time profile detected by Cooper et al. [4].

From the above studies, multiple peaks were usually recorded and each peak was potential to be the maximum one, depending on the combined effects of gas concentration and venting pressure. However, these studies did not provide sufficient details about the generation conditions of different overpressure–time profiles, as well as the generation mechanisms of the overpressure transients. In addition, the available models [3,10] and standards [11,12] for the prediction of vented gas explosion only considered single overpressure transient.

In the present study, vented gas explosion tests were conducted in a cuboid chamber filled with methane–air mixtures of different composition. The primary objective of this study is to investigate the generation mechanisms of the dominant overpressure transients, as well as the effects of concentration and venting pressure on each of them. In addition, the explanation for the four types of overpressure–time profiles and their corresponding generation conditions are presented.

2. Experiment

2.1. Test setup

A custom-designed 2 m × 2 m × 3 m reinforced concrete chamber as shown in Fig. 2, with a design pressure limit of 600 kPa (gauge pressure), was constructed. An igniting pill was hung at the center of the chamber that was 1.5 m above the floor and 1 m off the four walls. It was ignited by a synchronous detonator 100 m away, and the energy of the pill was about 100 mJ. The vent covers were mounted on a square window frame on the front wall of the test chamber, and clamped with a steel frame to form a rigid boundary with an effective venting area of 0.64 m^2. An infrared gas analyzer (QGS-08C, Nanjing Xinfen, China), with a measuring range of 0–15 vol.% and accuracy of 0.1%, was employed to measure methane concentration. An explosion-proof fan (CBF-300, Zhejiang Dafeng Blowers, China) was installed in the chamber. At a constant fan flow of 0.8 m^3/s, the characteristic time for mixing is estimated to be 15 s. Therefore, 20–30 min of continuous mixing prior to each test was sufficient to ensure homogeneity of gas composition in the entire chamber. The sliding door in the wall was a steel plate that could be drawn up through a fixed pulley. The overpressure were recorded by six piezoresistive pressure sensors (CYG 1409, Kunshan Shuangqiao Sensors, China), with a measuring range of −100 to 300 kPa (gauge) and 0.5% accuracy. Considering the high temperature and intense light inside the chamber during the explosion, all sensors were equipped with water-cooling circulation systems and clear filter to protect the sensors and ensure the reliability of the recorded data. Sensor 1, 2 and 3 were mounted on the front wall at the height of 0.2 m, 0.8 m and 2.5 m along the mid-line of the wall, respectively. Sensor 4 and 5 were mounted off the center line 0.65 m and 0.9 m. Sensor 6 was located at the center of the back wall. Signals from the pressure sensors were registered by the data acquisition instrument (Donghua 5927, Donghua

Table 1
Summary of the various overpressure transients in vented gas explosion.

Literatures	Physical events						
	Failure of the vent cover	Venting of the burned gases	Unburned gas flow through the vent	External explosion	Maximum flame area	Reverse flow after external explosion	Coupling between acoustic mode and flame
Overpressure transients							
Cooper et al. [4]	ΔP_1			ΔP_2	ΔP_3		ΔP_4
Guo et al. [5]	ΔP_1	ΔP_2			ΔP_3	ΔP_4	
Fakandu et al. [6]	ΔP_{burst}		ΔP_{fv}	ΔP_{ext}	ΔP_{mfa}	ΔP_{rev}	ΔP_{ac}
Chen et al. [7]	ΔP_1			ΔP_2			
Chow et al. [8]		ΔP_1	ΔP_b	ΔP_2			
Bauwens et al. [9]				ΔP_{ext}			ΔP_{vib}

Please cite this article in press as: Bao Q et al. Effects of gas concentration and venting pressure on overpressure transients during vented explosion of methane–air mixtures. Fuel (2016), http://dx.doi.org/10.1016/j.fuel.2016.01.084