Fuel 220 (2018) 471–480

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Confined explosion of methane-air mixtures under turbulence

Sazal K. Kundu, Jafar Zanganeh*, Daniel Eschebach, Yusuf Badat, Behdad Moghtaderi

Priority Research Centre for Frontier Energy Technologies & Utilisation, Discipline of Chemical Engineering, School of Engineering, Faculty of Engineering & Built Environment, University of Newcastle, Callaghan, NSW 2308, Australia

ARTICLE INFO

Keywords:
Methane-air explosion
Confined space
Turbulence in explosion
Process industry
Turbulence burning velocity
Damköhler's correlation

ABSTRACT

In this study, a large-scale investigation of completely confined methane-air explosions was conducted in a 1-m^3 spherical explosion chamber. The effects of turbulence and explosive powders on explosion parameters such as the deflagration index, maximum explosion pressure and burning velocity were examined. Theoretical calculations were conducted and are presented alongside the experimental data. The study suggests that the presence of turbulence increases the maximum explosion pressure. The values of the deflagration indices and burning velocities were found to be increased by the turbulence. The presence of an explosive powder provides similar effects to turbulence, and the values of the maximum explosion pressure, deflagration index and burning velocities increased with increases of the mass of the explosive powders. The magnitude of the turbulence generated in the explosion chamber was determined theoretically by employing Damköhler's correlation.

1. Introduction

Test data for large-scale explosions of methane-air mixtures in turbulent conditions is extremely valuable in addressing real world explosion hazards. Methane is the primary component of natural gas, which is used for household cooking in many countries around the world. In household spaces, the windows are often kept closed and the room condition nearly reaches a confined space. If there is a leak in the gas-line, the natural gas moves to the attics and dead air spaces of the room as natural gas is lighter than air [1]. Eventually, the whole room gets filled with a flammable gas-air mixture in its explosive condition. The presence of a running fan in a household room assists in the faster mixing of the gas-air and establishes a turbulent mixture of gas and air which potentially increases the explosivity of the mixture. Any source of ignition or any attempt at ignition, such as the initiation of a gas oven, can lead to an explosion, and even a mass killing. Test data for large-scale explosions can assist in addressing explosion hazards like these, as household rooms are usually of large volumes (typically larger than 25 m^3).

Several accidents due to indoor natural gas explosions have been reported in the media [2–5] and discussed in the literature [6,7]. A very recent natural gas explosion (24 Feb 2016) in a house in Stafford Township in New Jersey, USA, levelled the house and injured 15 people, where the explosion was originated from an underground gas-line leak [5]. The natural gas built up in the basement and the explosion occurred when the gas-air mixture came in touch with an open flame from an appliance. The explosion was so intense that the sound of the explosion could be detected 15 km away from its origin [8].

The mineral and fossil fuel extraction zones are nearly confined spaces. A number of methane-air based explosions have occurred in gold mines [9,10]. One of the most devastating gold mine accidents due to a methane gas explosion occurred in 1986 in the Kinross gold mine, South Africa, which took 177 lives. The numbers of methane gas explosions in coal mines that have occurred is several times than that of gold mine explosions in human history and around the world [11–13]. The magnitudes of the gas explosions in coal mines were later heightened by coal dust. The highest number of fatalities in human history due to a coal mine explosion occurred at the Benxihu Colliery in China in 1942, killing 1549 people [14]. In Australia, the deadliest coal mine explosion occurred at the Mount Kembla Mine in 1902, leaving 96 people lifeless [15].

Closed vessels are commonly employed in the process industries. Any mixture of flammable gas and air in these vessels can explode in the presence of an ignition source such as static electricity. Explosions in an enclosed space can lead to significant damage to lives and cause serious economic loss [6]. All these scenarios emphasise the necessity of understanding the explosion characteristics of methane-air mixtures in confined and turbulent conditions, so that the developed knowledge can be applied in addressing the real-world explosion hazards.

The explosion phenomena of a particular flammable gas-air mixture in a closed vessel can be explained by a number of parameters, including the maximum explosion pressure (P_{max}), the volume–normalised maximum rate of pressure rise or the deflagration index (K_G) and the explosion time [16,17]. The highest pressure attained in an

* Corresponding author.
E-mail address: jafar.zanganeh@newcastle.edu.au (J. Zanganeh).

https://doi.org/10.1016/j.fuel.2018.02.043
Received 2 December 2016; Received in revised form 1 December 2017; Accepted 8 February 2018
0016-2361/

Symbols			
P_{max}	maximum explosion pressure (bara or barg)	S_L	laminar burning velocity (cm s^{-1})
P_o	initial pressure (bara)	$S_{L,r}$	laminar burning velocity at reference condition (cm s^{-1})
P_r	reference pressure (bara)	S_T	turbulent burning velocity (cm s^{-1})
V	volume of the vessel (L or m^3)	φ	equivalence ratio (dimensionless)
dP/dt	rate of pressure rise (bar s^{-1})	α	temperature exponent (dimensionless)
$(dP/dt)_{max}$	maximum rate of pressure rise (bar s^{-1})	β	pressure coefficient (dimensionless)
K_G	deflagration index (bar.m s^{-1})	u'	rms value of turbulent velocity fluctuation (m s^{-1})

explosion test is termed the maximum explosion pressure, while the duration between the ignition time and the maximum explosion pressure attainment time is known as the explosion time. The deflagration index can be defined as:

$$K_G = (dP/dt)_{max}\cdot(V)^{1/3} \tag{1}$$

where $(dP/dt)_{max}$ is the maximum rate of the pressure rise obtained in an explosion test unit and V is the volume of that unit [18].

While a number of studies have been conducted with methane-air mixtures employing small-scale apparatus, only limited studies can be found in the literature that have employed large-scale apparatus. Cammarota et al., Salzano et al. and Bartknecht, in different studies, employed a vessel of 5 L to understand the explosion behaviours of methane-air mixtures [19–21]. Vessels of larger volume than 5 L were also employed in several studies. Cashdollar et al. employed both 20 L and 120 L volume vessels in explosion studies [22]. In general, the data obtained from vessels of various volumes and geometries have varied significantly.

The present work aims to provide an understanding of the explosions of methane-air mixtures in a confined 1-m^3 spherical vessel under turbulence. In a real-world scenario, turbulence may be present in a confined space due to the presence of rotating devices such as fans, blowers, mixers, agitators, etc. A spherical geometry was chosen for this examination as vessels of this geometry produce higher explosion pressures compared to vessels of other geometries. Various explosion parameters were theoretically predicted and compared with the experimental data obtained from the large-scale spherical explosion vessel employing various pyrotechnic ignition energies. The explosion times and the rates of the pressure rises are also estimated and presented in the article.

2. Experimental

The 1-m^3 sphere explosion apparatus employed in the investigation was sourced from ANKO Trading Limited (Fig. 1). The maximum operating pressure of the system was 30 barg and two dynamic pressure transducers (Kistler 601C) were fitted. The explosion chamber included a water cooling circuit which was driven by a water cooling block consisting of a pump and a radiator (see Fig. 2). One thermocouple (K type) was incorporated with the water cooling system to measure the water jacket temperature. Another thermocouple (K type) was integrated in the apparatus in order to measure the internal vessel temperature. The vessel door was opened and closed via a pneumatic system, as illustrated in Fig. 1.

The apparatus consisted of two identical pressurised chambers – the volume of each was 5.4 L. These chambers were originally designed for dust dispersion to the vessel. Only one chamber was employed in this study and it functioned as a turbulence generator. The inside shape of the turbulence generator was a cone and cylinder shape. It was programmed to pressurise to 21 barg with a mixture of air and methane, as illustrated in Fig. 2, and the other turbulence generator was kept idle. In the present study, no dust was introduced. The vessel was operated in 'hybrid' mode, with a 0 g.m^{-3} dust concentration, since this was the only available mode to complete a gas only experiment on the apparatus, which is the standard design for dust explosions. Methane was introduced via a 21 barg pressured line according to the partial pressure method as programmed in the manufacturer provided software (ANKO Dust Explosion Plotter – version 2.1.2.0). In this methane introduction process, the vessel was first vacuumed to a certain pressure value, depending on the desired methane concentration, and then the methane was introduced. In the turbulence generator, primarily methane and then air were introduced using the partial pressure method, and the

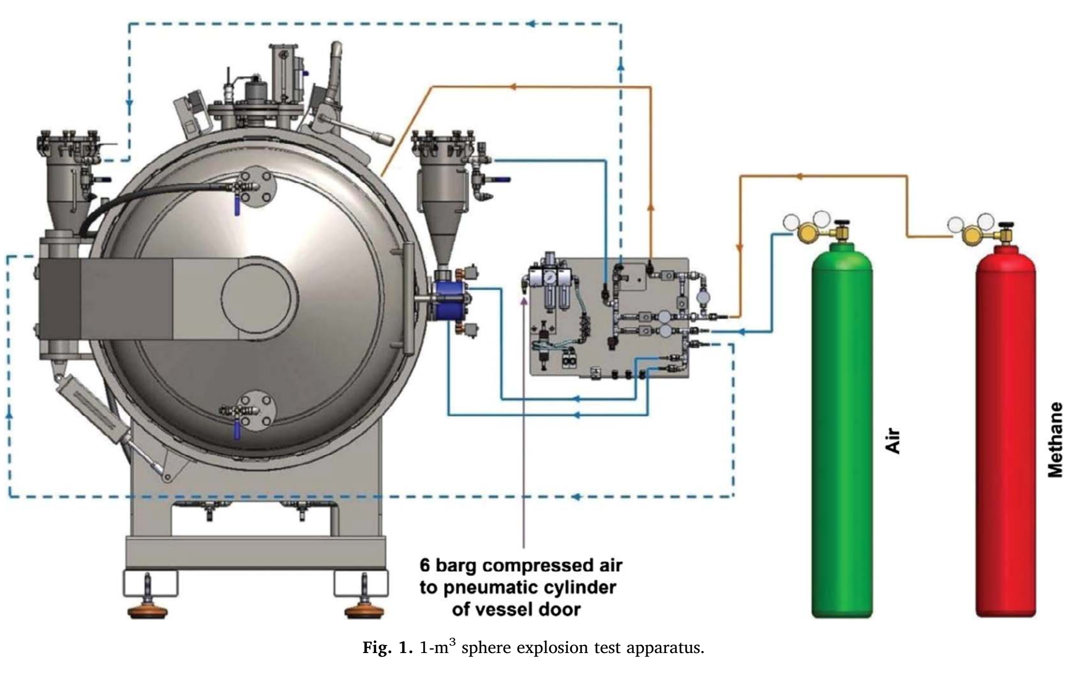

Fig. 1. 1-m^3 sphere explosion test apparatus.