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Deflagration of premixed methane–air in a large scale detonation tube

Mohammed J. Ajrash, Jafar Zanganeh*, Behdad Moghtaderi

The Frontier Energy Technologies Centre, Chemical Engineering, School of Engineering, Faculty of Engineering & Built Environment, University of Newcastle, Callaghan, NSW 2308, Australia

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ABSTRACT

Methane explosion hazards in pipes are of pivotal concern in chemical plants. Accurate knowledge of flame deflagration and its behaviours are required to reduce the consequences of accidental fires and explosions. Considering a lack of experimental work exists in large scale methane-air deflagration systems, a detonation tube (30 m long) was facilitated at the University of Newcastle to cover the knowledge gap in terms of boosting flame deflagration of low methane concentrations and also examining flame deflagration characteristics with different reactive lengths (3, 6, 12 and 25 m). The feature of injecting methane at varied reactive sections (RS) was achieved using a balloon isolation system, a 50 mJ chemical ignitor used to ignite the initial explosion section. The results revealed that stagnation pressure gradually increased, from 2.03 bar to 3.77 bar then 4.57 bar, with increasing RS length from 3 m to 6 m then 12 m, respectively. There was no significant influence of 1.25% or 2.5% methane concentrations on dynamic or stagnation pressures, however, they extended the travelling flame distance by about 3 m for RS lengths of 12 m and 25 m. At 9.5% methane concentration and for a RS of 12 m a state of fast deflagration was observed, associated with 5 bar pressure rise. The pressure wave up to 6.5 m was only a few milliseconds (about 15 ms) ahead of the flame for almost the full methane concentration range, however, after this point the gap between the pressure wave and the flame significantly varied in accordance to the methane concentration, where the data analysis at 15 m indicated that for 9% methane concentration the flame was only 21 ms behind the pressure wave, and for 5% and 15% methane concentration the flame was behind the pressure wave in the range of 55–93 ms. Due to the limited length of the DT compared with the large volume of methane injected, there was no significant influence on the flame deflagration properties when extending the RS length from 12 m to 25 m, as the mixture initially located after 12 m pushed out through the open end.

1. Introduction

A pivotal concern of process industry safety is the prevention of potenial explosions. Understanding the criteria of the fire and explosion events and their consequences, however, is contributing to increasingly sophisticated design safety for the process industries (Eckhoff, 2013). As mining, oil and gas industry plants are typically congested, accidental fires and explosions are enhanced, causing massive loss of life and property. According to Khan and Abbasi (1999), there were about 2584 fatalities and 1800 injuries caused by chemical process accidents in the period between 1981 and 1997. Fugitive methane and natural gas (Oran et al., 2015) caused 279 fire accidents costing about $41 billion in property in the period between 1907 and 2007. As a part of these statistics, there were 2834, 3330 and 709 fatalities caused by coal mines, oil and gas industry fires and explosions, respectively (Sovacool, 2008). The majority of accidental fire and explosion events in coal mines

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* *Corresponding author at*: C Block-NIER Building, University Drive, Callaghan, NSW 2308, Australia.
E-mail address: jafar.zanganeh@newcastle.edu.au (J. Zanganeh).

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are caused or enhanced by methane and natural gas, as reported by a number of researchers (Ajrash et al., 2016a; Akgun, 2015; Dhillon, 2010; Kundu et al., 2016; Lee, 2003; Lowesmith and Hankinson, 2013; Market et al., 2015; Tu, 2011; Wang et al., 2014). It is important to advise that 85%–99% of natural and fugitive gases consist of methane (Gamezo et al., 2012). An explosion is generally described as a sudden release of energy due to a chemical reaction with regard to the types of reactants (Ajrash et al., 2016b; Bai et al., 2011; Cashdollar et al., 2000; Eckhoff, 2013; Kundu et al., 2016; Sanchirico et al., 2011). In current research, the term explosion may refer to any combustion increase in the pressure of the system by 3% due to the fuel combustion, which may implicitly include both the deflagration and/or detonation (Ajrash et al., 2016c; Yuan et al., 2014).

1.1. Methane air mixture explosions in cylindrical vessels

Abel (1869) first discovered the pressure development of gases in tubes. However, Berthelot and Vieille (1881) were the first researchers who systematically measured the deflagration and detonation in tubes of hydrocarbon gases. Later, Mallard and Le Chatelier (1881) and Jouguet and Chapman (1913) theoretically and experimentally explained the phenomena of detonation in tubes. Mason and Wheeler (1920, 1917) are considered the earliest researchers to give attention to the characteristics of methane explosions in tubes. They observed that the flame velocity continually increased while traveling in the tube. The study was performed by using a laboratory scale setup with a tube of 50 mm diameter and 5 m long, closed at the ignition end, and open at the other end. In spite of using a relatively short tube and a small L/D ratio (3.65 m long and 0.305 m diameter), the phenomena of detonation was formed at stoichiometric methane air mixtures using a high energy explosive detonator, sodium chloride and ammonium nitrate (Payman et al., 1937). Kogarko (1958) also used higher energy explosive ignitors, a longer tube (11.2 m), and a similar diameter to the setup used by Payman et al. The most important conclusion was that the deflagration to detonation transition was observed in the range of 6.3%–13.5% of methane in air. In another study, the detonation present for methane concentration in the range of 8%–14.5% Wolanski et al. (1981).

Phylaktou et al. (1990) documented the flame speed and pressure rise rate for methane air mixture explosions in a vertical closed tube (1.64 m long, 21.6 L/D). Ignitors of 16 J were used and located at one end of the tube, with the pressure transducer mounted at the second end. To ensure a homogeneous mixture, an external circulation pump was used. Phylaktou et al. (1990) exhibited that at 10% methane, the pressure time history showed four phases. The first phase (short phase) represented the flame expanding from the ignitor. A rapid pressure elevation was noticed in the second phase, where the pressure increased from 1 to 3 bar in 30 ms. The third phase starts when the pressure rise and the flame speed are arrested and persist almost at constant values. The last stage was when the system suddenly cooled, and was associated with oscillations in the pressure readings. Finally, the pressure rise recoded was 6.9 bar when the equivalence ratio was equal to one (Phylaktou et al., 1990). Six one end open tubes with different diameters were used by Knystautas et al. (1982) to illustrate the influence of the tube diameter on the flame deflagration. The oxygen, nitrogen and fuel were introduced into the vacuum pressure system through a calibrated rotameter. The explosion was initiated through an exploding wire delivering 200–2500 J to the system.

The deflagration to detonation transition phenomena did not occur in all tubes at air stoichiometric conditions. Knystautas et al. extrapolated from β versus critical diameter that methane detonation may occur at the air stiochoimetric condition when the tube diameter is larger than 0.24 m. Kindracki et al. (2007) examined the effects of location of the initial ignition positions on the pressure rise of methane explosions in a horizontal tube 1.325 m long. Results were obtained for three concentrations, 7%, 9% and 12%. They also noticed that the position of the ignitor plays an important role on the flame speed and pressure profile, where the maximum pressure was recorded when the ignitors were in the middle of the tube. This was attributed to the fact that when the ignitor was at the end, a longer time is needed for the products to exchange the heat with the vessel walls.

The dynamic pressure of methane flame deflagration was highlighted by Wei et al., 2009. The experimental work was carried out on a 30 m long propagation tube with a 0.5 m diameter. Methane gas was used in the experiments, and each explosion was initiated by a 50 mJ chemical ignitor. The aim of the work was to address the static and dynamic pressure in a long propagation tube. Two approaches were used: firstly, the tube was fully open from one side; and secondly, the tube was closed by a structure. The two main outcomes could be summarized as follows: the maximum pressure of the experimental work was less than the theoretical estimations; and the measured values of the total pressure were very close to the theoretical values from the summation of the static and dynamic pressures. Additionally, there was no significant impact of the volume of the gases in the explosion on the static pressure when the tube was fully open.

In research work by Li et al. (2012), the interactions of methane flame velocity and the pressure wave were experimentally explored. The length of the tube was 12 m and the dimensions were 80 mm by 80 mm. A spark ignitor of 10 kJ was employed to ignite the methane air mixture. The results showed that the closed pipe had an obvious impact on the transition of the methane deflagration flame due to the pressure wave reflection. However, a number of researchers have studied the acceleration and the deflagration to detonation transition (Gamezo et al., 2012; Jiang et al., 2016; Kessler et al., 2010; Kuznetsov et al., 2002a, 2002b; Moen and Lee, 1982; Peraldi et al., 1988; Porowski and Teodorczyk, 2013; Salzano et al., 2002; Zipf et al., 2014). Other theoretical research has studied flame transport behaviour in vessels and tubes (Keshavarz and Oftadeh, 2002; Oran et al., 2011; Valiev et al., 2009; Wang et al., 2013; Zhang et al., 2011).

1.2. Aim of the research

The main aspect of this work is to cover the lack of experimental data on methane-air mixture deflagration in large-scale systems. The previous experimental work related to the topic could be criticized as follows; only few studies reported the methane flame deflagration in a large scale tube, most of them used a high energy ignition source that could overdrive the methane flame deflagration and give inaccurate results; And the values of dynamic and stagnation pressure were not reported in line with the flame deflagration properties. Finally, it has not been shown how low methane concentrations assist in accelerating flame deflagration of explosions in tubes. This case may be present in process and extractive industry (i.e. ventilation air methane), where the concentration of methane is typically less than 1.25%, but may rise up in abnormal conditions. The existing literature shows that there are only a few works previously highlighting the consequences and properties of methane-air mixture deflagration in a large-scale system. In 2015, a large-scale detonation tube system was built at the University of Newcastle (UoN) to cover the existing knowledge gaps needed to design a sophisticated capture duct able to trap and mitigate explosions and their consequences. The first aim of this work was to deliver valid data for the design of suitable mitigation and alarm systems. The second aim was to examine the propagation and deflagration of flames at low concentrations (below lean limit). Additionally, the study examines the front flame and pressure wave velocity results for variable tube explosion volumes. Finally, the static and dynamic pressures will be discussed for all of the above scenarios and expectations for the maximum destructive forces of varied methane concentrations under variable tube methane explosion volumes are given.

2. Experimental setup and methodology

2.1. Detonation tube and diagnostics

The detonation tube used in this study consisted of eleven sections with a diameter of 0.5 m, a total length of 30 m, and a 6 m silencer attached at the end of the tube to reduce the noise of the explosions (see Fig. 1).