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Explosion characteristics of methane–air mixtures in a spherical vessel connected with a duct

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ABSTRACT

With the aim of exploring explosion characteristics of methane–air explosive mixtures in a ducted vessel, a 20 l spherical vessel connected with a 2813 mm long duct was employed. The experimental setup was comprised of a wafer check valve, which kept the methane–air mixture initially confined and opened at the time of explosion. The system introduced turbulence to the gas mixture during operation and pyrotechnic igniters were employed in the investigation. This approach assisted to obtain data that can be correlated with real world ducted explosion accidents where the explosion initiates in the presence of strong ignition energies and in turbulent states of methane–air mixtures. This study shows that the explosion severity can be very high in the turbulent field of methane–air mixture and in the presence of strong ignition energies. The pressure rise in the vessel and the flame speed along the length of the duct were found to be higher in the present study when compared to data obtained with quiescent methane–air mixtures and low ignition energies. The impact of the duct length and pyrotechnic igniters' energy on reduced peak explosion pressure was characterised. The rate of pressure rise, a parameter linked to the burning rate, increased from the ducted to the vented configurations of the explosion test units.

1. Introduction

In process industries, flammable gases and vapour may be present in vessels and storage tanks. These process units may contain feed material, product or fuel. In order to transport materials to and from these vessels and tanks, they need to be connected with pipelines (Kundu, 2010). With the advancement of control systems, these vessels and tanks are often connected with electrical sources and any naked electrical connection may become an ignition source in these systems (Chou et al., 2015). If there is any leak in the vessel/tank or pipeline, or any loose connection is present in the pipeline, oxygen may be present in the system. All of these conditions are capable of fulfilling the requirements for an explosion.

Pockets of methane gas are often present in coal mines. These mine areas may be connected with ducts or channels. In the presence of an ignition source, these areas may mimic an explosion model of a vessel connected to a duct. Several accidents in underground coal mines have been reported in the literature (Ajrash et al., 2016a,b; Kundu et al., 2016; Qin et al., 2016; Zhang and Ma, 2015) which have motivated researchers to understand the explosion characteristics of methane–air mixtures by employing explosion units of various geometries (Kundu et al., 2016). Therefore, understanding explosion characteristics in vessels with connected ducts is expected to provide important information in order to design proper safety measures in the process industries, including coal mines.

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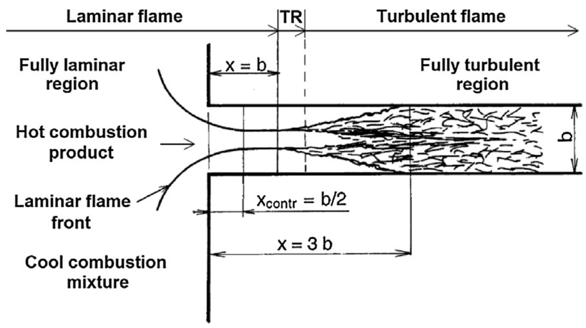

Fig. 1 – Illustration of the behaviour of a flame entering from a vessel to a duct (Iida et al., 1985).

Ducts are often deliberately integrated with enclosed process units with the aim of reducing any potential damage caused by explosions of flammable substances (Foiles, 2004; Kasmani et al., 2013; NFPA-68, 2007; Russo and Di Benedetto, 2007), where the integrated duct is known as vent duct. The one end open duct usually reduces the severity of an explosion in the vessel by reducing the explosion pressure, and more importantly, discharging hot and toxic materials in a safe location if an explosion occurs.

When a flame propagates from a vessel to a duct, the properties of the flame are affected at the entrance of the duct (see Fig. 1). The flame entering into the duct propagates in a constricted pattern where the flame is surrounded by cold unburned mixture. Downstream of the duct, the flame broadens covering the full cross-section of the duct (Iida et al., 1985).

Previous studies suggest that integrating a duct with a vessel increases pressure rise in the vessel during an explosion when compared to pressure rise in a simply vented vessel. In contrast, the pressure rise in a confined vessel is higher than in a vessel connected with a duct (NFPA-68, 2007). The modification of either a vented or confined vessel to ducted vessel introduces the severity of the explosion in the connected duct (Bouhard et al., 1991; Gardner et al., 1988; Kordylewski and Wach, 1986). While investigating the explosion characteristics of propane–air mixtures in a ducted vessel employing a duct of 200 mm length, 110 mm width and 70 mm depth, Iida et al. (1985) found that a fully turbulent flame forms at three times the distance of the width of the duct ($x = 3b$), as illustrated in Fig. 1. The evidence of a fully turbulent flame was confirmed by a schlieren image captured by Iida et al. and the image identified an intensive mixing of unburned fuel–air mixture and hot products from the combustion. The generated turbulence increases the burning rate, and for longer pipes a transition from deflagration to detonation can occur (Kosinski and Hoffmann, 2006; Ponizy et al., 2014; Russo and Di Benedetto, 2007). The mechanism of the generation of violent flames in a ducted vessel thus inspired a number of researchers to undertake explosion studies in ducted vessels with various flammable materials (Molkov, 1994; Russo and Di Benedetto, 2007; Tamanini and Valiulis, 1996).

As presented in Fig. 1, the combustion products and the flame propagate from the vessel to the duct, and the pressure in the vessel reduces. The pressure profile thus obtained from the vessel, with respect to time, may be described as a reduced explosion pressure profile (Barton, 2002). In the duct, the pressure rise, with respect to atmospheric pressure, occurs due to ongoing combustion of the discharged material from the vessel. The pressure profile thus developed in the duct as a function of time is simply defined as explosion pressure profile.

With the aim of exploring the characteristics of explosions in ducted vessels, several researchers employed propane–air mixtures (Bouhard et al., 1991; Ferrara et al., 2005; Iida et al., 1985; Kasmani et al., 2013; Ponizy et al., 2014; Willacy et al., 2007). Investigations were also carried out with acetone–air (Benedetto et al., 2008) and town gas–air (Kordylewski and Wach, 1986) mixtures (town gas is a gas mixture and includes mainly methane and hydrogen with smaller fractions of CO_2 and CO). Vessels of various geometries, such as cylindrical (Ferrara et al., 2008; Ponizy et al., 2014) and spherical (Kordylewski and Wach, 1988) shapes, were employed in prior research. The ducts utilised in the various studies mainly had circular cross-sections (Ferrara et al., 2008; Kasmani et al., 2013), but non-circular ducts were also employed (Iida et al., 1985).

While a number of studies were undertaken employing propane–air mixtures in ducted-vessels, only limited data is available in open literature for explosion studies with ducted vessels for methane–air mixtures. The previous examinations in confined vessels showed that spherical vessels with central ignition produced the highest explosion pressures. For vessels of other geometries and other ignition positions, the developed flame partially makes contact with the vessel wall and, as a consequence, due to heat loss the peak explosion pressure reduces (Bradley and Mitcheson, 1976, 1978; Garforth, 1976). However, in earlier explosion studies of methane–air mixtures with ducted vessels, cylindrical vessels were mainly employed (Ferrara et al., 2008; Kasmani et al., 2013). Therefore, investigations with non-cylindrical vessels connected with ducts will provide enhanced understanding of the explosion phenomena of methane–air mixtures in tunnels or chimneys that are present in mines of mineral extraction and process industries. Process safety researchers and engineers will gain vital data in addressing explosion hazards in those industrial zones.

Pyrotechnic igniters were employed in the present investigation. The igniters with higher ignition energies are constructed with higher amounts of ignition powders and they produce higher flame areas once they get ignited. The overall burning rate increases with the increase of flame area (Lee and Guirao, 1982); therefore, explosion pressure increases with an increase of the ignition energy. For high energy pyrotechnic igniters, this effect diminishes because of the thermodynamic limit of explosion pressure.

With the aim of exploring the explosion characteristics of methane–air mixtures in a ducted vessel, a spherical vessel was employed in the present investigation. To the best of our knowledge, we are reporting the first explosion studies of methane–air mixtures employing a spherical vessel integrated with a duct. The effects of the ignition energy, the duct length and the concentration of methane on pressure rise and flame speed were investigated. The variations of the rates of pressure rise in simply vented and ducted vessels, and the link of this explosion parameter with the burning rate, are explored and discussed.

2. Experimental

A 20 l explosion sphere was employed in this investigation. The test vessel includes a closed circuit water cooling system. Piezoelectric pressure transducers (Kistler 701A) are mounted to measure the pressure rise during the explosion tests.

In order to achieve the goals of the present investigation, the 20 l sphere was modified at its viewing port (see