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Explosion pressure measurement of methane-air mixtures in different sizes of confinement

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ABSTRACT

This article reports the results of an experimental study on explosion pressure measurement in closed vessel deflagration for methane-air mixtures over its entire flammable range at standard pressure and temperature in vessels with variable geometry and size- 20-L spherical, 27-L cubical, 0.8 m^3 rectangular and 25.6 m^3 spherical-under quiescent conditions using electric spark (3 J) as ignition source. The outcome of the study is comprehensive data that quantify the dependency of explosion severity parameters on gas concentration and vessel volume. The information is required to quantify the potential severity of an explosion, design the vessels able to withstand an explosion and to design explosion safety measures for installations handling this gas. The data presented include maximum explosion pressure, explosion time and rate of explosion pressure rise in terms of deflagration index over a range of methane-air equivalence ratio (φ: 0.53–1.52). The maximum explosion pressures are: 8.6, 8.4, 8.2 and 8.0 bar in 20-L sphere, 27-L cubical vessel, 0.8 m^3 rectangular vessel and 25.6 m^3 sphere, respectively, at φ=1.05. Time to reach the maximum explosion pressure varies from 80 ms in 20-L sphere to 680 ms in 25.6 m^3 sphere. The deflagration index values are: 82, 84, 86 and 106 bar m/s in 20-L sphere, 27-L cubical vessel, 0.8 m^3 rectangular vessel and 25.6 m^3 sphere, respectively, at φ=1.05. The deflagration index increases with increase in size of the test vessel.

1. Introduction

Large quantities of methane are produced in the industry today and used as fuel for ovens, water heaters, kilns, automobiles, turbines and other things, and considered green energy system. Methane is the main component of natural gas which is one of the promising clean alternative fuels. Gas-air mixtures are formed in industries and may lead to explosion in presence of an ignition source. The assessment of explosion hazard of such mixtures is important based on values of safety parameters under various conditions. Explosions of fuel-air mixtures in enclosures are characterized by specific characteristic parameters - explosion pressure, P_{exp}, defined as the highest pressure reached during an explosion in a closed volume at a given fuel concentration, and the maximum explosion pressure, P_{max}, found as the highest P_{exp} over the flammable range, maximum rate of rise of explosion pressure, $(dP/dt)_{max}$ and time to reach to maximum explosion pressure,θ_{max}. These characteristics are needed for explosion risk assessment, pressure vessel design for explosion containment and design of effective safety devices - explosion suppression system, explosion relief venting - for handling of methane in closed vessel to ensure active protection of pressure vessels where flammable mixtures are formed (Fairweather and Vasey, 1982; Maisey, 1965; NFPA 69, 2008; Razus and Krause, 2001). The values of these parameters are useful for emergency planning specially for developing scenarios where emergency relief or external heat transfer may be inadequate. The explosion pressures and explosion times are used for validation of propagation wave models and laminar burning velocity prediction in various conditions (Dahoe and de Goey, 2003; Oancea et al., 1994; Razus et al., 2006) and characterization of transmission between interconnected vessels (Razus et al., 2003).

The experimental results of explosion data measurements depend on many different parameters of the investigated process, such as the energy and type of ignition source, size and shape of explosion chamber, initial temperature and pressure and composition of flammable mixture. Maximum explosion pressure is determined as the highest value of pressure developed by a deflagration after a series of deflagration tests done over wide range of concentration (EN 13673-1, 2003; EN 13673-2, 2005). From this series of test the value of maximum rate of pressure-rise can be obtained from the pressure-time history. In order to compute (dP/

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$dt)_{max}$, the experimentally measured pressure signals are numerically differentiated. The dependence between maximum pressure rise and volume of vessel is known as the cubic law, giving approximations in scale-up of the vessel volume when all other parameters like pressure, temperature, turbulence, ignition energy, etc. are kept constant. The characteristic value that describes closed vessel combustion is the deflagration index, K_G, also known as pressure-rise coefficient. If the maximum rate of pressure-rise is measured in a vessel in a volume other than 1 m^3, equation (1) has been proposed to normalize the value for calculation of K_G (Barknecht, 1981).

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

where,

P - Pressure, bar
t - Time, sec
V - Volume, m^3
K_G- Deflagration index, bar.m/s
$(dP/dt)_{max}$-Maximum rate of pressure rise, bar/s.

Thus K_G is defined as the product of maximum pressure-rise $(dP/dt)_{max}$ during the combustion and a characteristic length, l_{char}, equal to the cube root of the vessel volume $V^{1/3}$. K_G factor is normally used to design explosion safety measures and to predict the consequences of explosion. The explosion pressure and rate of pressure-rise are influenced by size and geometry of the ignition vessel, the directions of flame spread and turbulence (Barknecht, 1981; Mashuga and Crowl, 1998). The value of K_G is therefore not a constant and varies depending on test conditions such as type and amount of ignition energy, volume of test vessel, and other test conditions.

The experimental results presenting maximum explosion pressure and deflagration index for stoichiometric methane-air mixtures using different sizes of vessels by different researchers (Barknecht, 1981; Cammarota et al., 2010; Cashdollar et al., 2000; Dahoe and de Goey, 2003; Gieras et al., 2006; Gieras and Klemens, 2009; Holtappels, 2002; Kunz, 1998; Mashuga and Crowl, 1998; Nagy et al., 1971; Pekalski et al., 2005; Prodan et al., 2012; Razus et al., 2006; Senecal and Beaulieu, 1998; Salzano et al., 2012; Sapko et al., 1976; Zabetakis, 1965; Zhang et al., 2014) presented in Table 1 show large discrepancies due to different sources of uncertainty. The experimental results from Federal Institute for Material Research and Testing (Holtappels, 2002) consists of experiments conducted by Federal Institute for Material Research and Testing (BAM), TU DELFT University and Institut national de l'environment industriel et des risques (INERIS).

Since the deflagration index is an intrinsic property of a premixture at certain conditions (i.e. at specific temperature and pressure) experiments conducted by different groups should provide nearly the same value of K_G for the same pre-mixture under similar conditions. Unfortunately due to different sources of uncertainty, there are substantial discrepancies in the deflagration index measured by different researchers for the same methane-air mixture (Table 1). The reported deflagration index ranges from 20 bar m/s measured in 5-L cylindrical chamber (Cammarota et al., 2010) to 110 ± 10 bar m/s in 25 m^3 spherical chamber (Nagy et al., 1971; Sapko et al., 1976). The values of deflagration index measured in 20-L sphere for stoichiometric methane-air varies from 30.4 to 86 bar m./s. Almost all the experiments for deflagration index measured were conducted in cylindrical or spherical vessels. When a cylindrical vessel is used, the unburnt mixture cannot be consumed completely by the propagating spherical flames as it reaches the inner wall of vessel. Therefore, both maximum pressure-rise rate and deflagration index are underestimated in experiments using cylindrical vessels. For larger volume, close to the volume used by industry maximum explosion pressures (7.6–7.7 bar) are reported in 25 and 204 m^3 vessels (Nagy et al., 1971; Razus et al., 2006a; Sapko et al., 1976). In 10 m^3 vessel P_{max} was 6.96 bar and $(dP/dt)_{max}$ was 18.2 bar/s which corresponds to K_G value of 39.2 bar m/s (Zhang et al., 2014). Faghih et al. (2016) report a computational study on explosion characteristics of methane, hydrogen and their mixtures. They obtained deflagration index by numerical simulation of outwardly propagating spherical flames in closed vessels.

It has been reported in literature (Cashdollar et al., 2000; Britton and Chippett, 1985; NFPA 68, 2007) and some of the data presented in Table 1 also indicate that in case of initially quiescent gas, the normalized K_G index is found not to be constant but to increase with vessel volume. The increase in K_G is related to various flame acceleration effects (Chippett, 1984; Solberg et al., 1981; Swift, 1983). Thus a single value of K_G for a particular set of test conditions is only one among a series of values that vary over the range of test conditions. Table 1 shows that K_G values determined in 40-L and 1.25 m^3 vessel are lower than values determined in other smaller volumes. But the K_G values of 1.25 m^3 are also higher than those of 40-L vessel. The shapes of these vessels may be responsible for this. Both the vessels are cylindrical but the height to diameter ratios is not suitable for the determination of K_G values of gas explosions. If one assumes spherical flame propagation from the ignition source only a small volume is taken by the flame when it reaches the vessel walls. In case of 40-L vessel the volume of spherical flame at this stage is 20 L, so that only half of the volume reacted. Due to pre-compression of the unburnt mixture, the amount of burnt mixture is less than half. The heat losses when flame touches the walls and the low amount of burned gas mixture lead to low K_G values. Such effects do not occur in spherical vessels and also in cylindrical vessels with H/D ratio of about 1. General volume dependence (increasing K_G values with increasing volume) is found if K_G values in 40-L and 1.25 m^3 vessels are compared.

Many processes, especially in the petrochemical industry operate in different volume of confinement. While the values of such explosion parameters at these conditions are essential to safety and reliable operation, they are nevertheless largely unavailable in open literature. The explosion data for methane gas from different sizes of vessels (5-L to 204 m^3) under varying experimental conditions (Table 1) are recommended for designing explosion safety measures for industrial units according to various standards (NFPA 68, 2007, NFPA 69, 2008) which are based on 1 m^3 or 20-L data. As discussed above, due to different sources of uncertainty, there are substantial discrepancies in the explosion severity characteristics measured by different researchers for the same methane-air mixture. Though methane might be the best examined gas regarding explosion safety, but until now not all dependencies and combustion behavior are known. To ensure also safe handling of methane in all situations it is important to know the safety related properties at all necessary conditions. The study will also add to safety data for control of dust explosions in coal mines. Most common dust explosion occurs in underground coal mines. In coal mine tunnel, coal dust explosion is usually caused by methane-air explosion. Moving at the speed of sound, pressure waves resulting from gas explosions lifts the deposited coal dust in the air. The gas flame reaches the coal dust causing a coal dust explosion which is more severe than the first one (Bidabadi et al., 2015; Yan-song et al., 2009).

The present research was undertaken to obtain comprehensive information on explosion pressure, explosion time and deflagration index of quiescent methane-air mixture in closed chambers of various sizes and different geometries at ambient temperature and pressure using identical ignition source and to examine the effect of