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Vented hydrogen–air deflagration in a small enclosed volume

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ABSTRACT

Since the rapid development of hydrogen stationary and vehicle fuel cells the last decade, it is of importance to improve the prediction of overpressure generated during an accidental explosion which could occur in a confined part of the system. To this end, small-scale vented hydrogen–air explosions were performed in a transparent cubic enclosure with a volume of 3375 cm^3. The flame propagation was followed with a high speed camera and the overpressure inside the enclosure was recorded using high frequency piezoelectric transmitters. The effects of vent area and ignition location on the amplitude of pressure peaks in the enclosed volume were investigated. Indeed, vented deflagration generates several pressures peaks according to the configuration and each peak can be the dominating pressure. The parametric study concerned three ignition locations and five square vent sizes.

Introduction

A major problem of this century is to reduce green house gases, pollution in cities and dependency on oil-based fuels. Hydrogen is seen as one of the best solutions as a clean energy carrier to answer to these three challenges. In order to be well accepted by the public, existing risks have to be clearly identified and safety standards have to be well established for systems working with hydrogen. If a leak occurs in such systems, a confined volume filled with hydrogen and air could appear in a part of the system and could be accidentally ignited. Then, it is of interest to improve the prediction of overpressure generated during an accidental explosion at small scale. Large-scale hydrocarbon–air vented explosion experiments have been widely studied; conversely it appears that only few papers deal with hydrogen–air vented explosions and more particularly at small scale. Large-scale vented experiments were performed by Kumar et al. [1,2] with 6 vol.% to 11 vol.% hydrogen in air mixtures in a 120 m^3 confined volume [1] and 6 vol.% to 42 vol.% hydrogen in air mixtures in a 6.5 m^3 volume [2]. Pasman et al. [3] have studied a stoichiometric hydrogen–air mixture in 1 m^3 volume. Bauwens et al. [4,5] and Chao et al. [6] have reported works in a 63.7 m^3 chamber with an 18 vol.% hydrogen in air mixture. Finally, Daubech et al. [7] have studied the vented hydrogen–air deflagration in a volume of 1 m^3 and 10 m^3 with 10 vol.% to 30 vol.% hydrogen in air mixtures. Detailed small-scale experiments found in the literature concern methane–air mixtures in cubic vessels with volumes of 5800 cm^3 and 54,900 cm^3 studied by McCann et al. [8]. More recently, Sato et al. [9] have performed propane–air vented explosion in a

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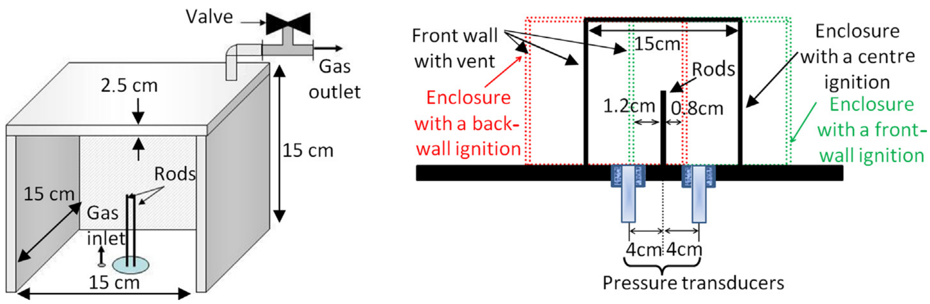

Fig. 1 – Front view scheme without front wall (left) and location of the cubic enclosure (right) for front-wall ignition (green), centre ignition (black) and back-wall ignition (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cubic enclosure of 4000 cm^3. Effects of ignition location on pressures generated during vented explosion were investigated by Kumar et al. [1], Bauwens et al. [4,5], Chao et al. [6] and McCann et al. [8]. During vented deflagration several pressure peaks appear according to the configuration, i.e. the vent area and the ignition location. These peaks have been observed and well identified by Cooper et al. [10]. Among the pressure peaks, two peaks can dominate the internal pressure; the first one is created by the external explosion (P_1) and the second one (P_2) by the internal combustion where flame-acoustic coupling occurs. In order to add data for vented explosion modelling, this paper will present the experimental results for small-scale vented explosions of a stoichiometric hydrogen–air mixture. The influence of vent area and ignition location on the pressure history and pressure peaks P_1 and P_2 were investigated. Indeed, several models allow evaluating the maximal overpressure generated inside the enclosure. The relevant standards are the NFPA 68 [11] and the European version EN 14994 [12], based on Bartknecht's equation [13] which has a limited range of application. The critical limitations are: the reduced pressure which must be higher than 10 kPa and lower than 200 kPa, the initial pressure before ignition must be lower than 20 kPa, the static vent activation pressures must be less than 50 kPa and the deflagration index K_G is limited to 55 MPa-m/s. Molkov [14–17] has proposed a dimensionless correlation to answer all these limitations. Similarly, Bauwens et al. [4] have published a physics-based model which allows to estimate the magnitude of each pressure peak P_1 and P_2.

Experimental setup

Experiments were performed in a cubic vessel (Fig. 1) with inner sides of 15 cm ($V = 3375$ cm^3). Laterals and top walls of 25 mm thickness are made of Plexiglas® in order to visualize the flame front propagation. Five square vent areas A_v were tested (225 cm^2, 81 cm^2, 49 cm^2, 25 cm^2 and 9 cm^2). The first one was obtained by removing the front wall. The other vents were realized with a centred square orifice on the front wall. The vent cover material was a thin polyethylene film, with a low failure pressure of about 3 kPa.

The ignition source was obtained by means of a spark generated between two rods. These rods were spaced of 1 mm and were 7.5 cm high, that is to say half of the height of the cubic vessel. The nominal energy delivered was estimated to 122 mJ. Three ignition locations were studied, back wall, centre and front wall. The back-wall ignition corresponds to rods located at 8 mm from the rear wall, that is to say opposite to the vent (red enclosure in Fig. 1) and the front-wall ignition corresponds to rods located at 12 mm from the wall with the vent (green enclosure in Fig. 1).

The enclosure was filled with a 30 ± 0.25 vol.% hydrogen in air mixture regulated by two mass flow controllers. The gaseous mixture was injected near the rods on the ground during a fixed time to flush the initial air through the gas outlet located on the top side. The initial turbulence was considered to be weak as the mixture was ignited two minutes after the enclosure was filled. The overpressure generated by the explosion was measured by means of piezoelectric transducers PCB Piezotronics. A thin silicon grease layer was applied on sensors to avoid thermal effects on the pressure measurement. All overpressure values given in the present paper are an average of three shots or more. An overpressure uncertainty of ±1.3% was obtained during calibration. The flame front propagation was followed with a high speed camera recording at 15,000 fps. All pressure histories were synchronized with the video frames with an uncertainty of ±33 μs.

Experimental results

The internal pressure in the enclosure was measured with two pressure transducers located at 4 cm from each side of the ignition source in case of centre ignition, and with one pressure transducers at 4 cm from the rods in case of front-wall and back-wall ignition (Fig. 1). A maximum of three main peaks were observed according to the vent area (or vent coefficient K_v) and the ignition location. The nondimensional vent coefficient K_v is given by the following relation: $K_v = V^{2/3}/A_v$. An example of pressure history with the presence of these three peaks is given in Fig. 2. A 1.5 kHz low pass filter was applied (blue) to the raw signal (black) to perform pressure peaks analysis (Fig. 2). This frequency allows to eliminate short duration pressure peaks which have to low impulse to produce damage (the frequency of acoustic oscillation is about 6.9 kHz in Fig. 2). These peaks were already identified and