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 this last decade, it is of importance to improve the prediction of overpressure generated during an accidental explosion which could occurs in a confined part of the system. In this aim, 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. The maximal overpressures measured in the enclosure, due to the external and internal combustion, were compared to models of the literature.

1.0 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 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 a 6% to 11% vol. hydrogen-air mixture in a 120 m^3 confined volume [1] and a 6% to 42% hydrogen-air mixture 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 a 18% vol. hydrogen-air mixture. Finally, Daubech et al. [7] have studied the vented hydrogen-air deflagration in a volume of 1m^3 and 10 m^3 with 10% to 30% vol. hydrogen-air mixtures. Detailed small scale experiments found in the literature concern methane-air mixtures in cubic vessels with volumes of 5800 cm^3 and 54900 cm^3 studied by McCann et al. [8]. More recently, Sato et al. [9] have performed propane-air vented explosion in a 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 modeling, this paper will first 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 actual standard is 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] has proposed a dimensionless correlation to answer all these limitations. Similarly, Bauwens et al. [4] have published a physic based model which allows to estimate the magnitude of each pressure peak P_1 and P_2. Then, the second objective of this paper is to compare the Molkov correlation and the Bauwens model to our experiments results.

2.0 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 centered square orifice on the front wall. The vent cover material was a thin polyethylene film, with a low failure pressure of about 3 kPa.

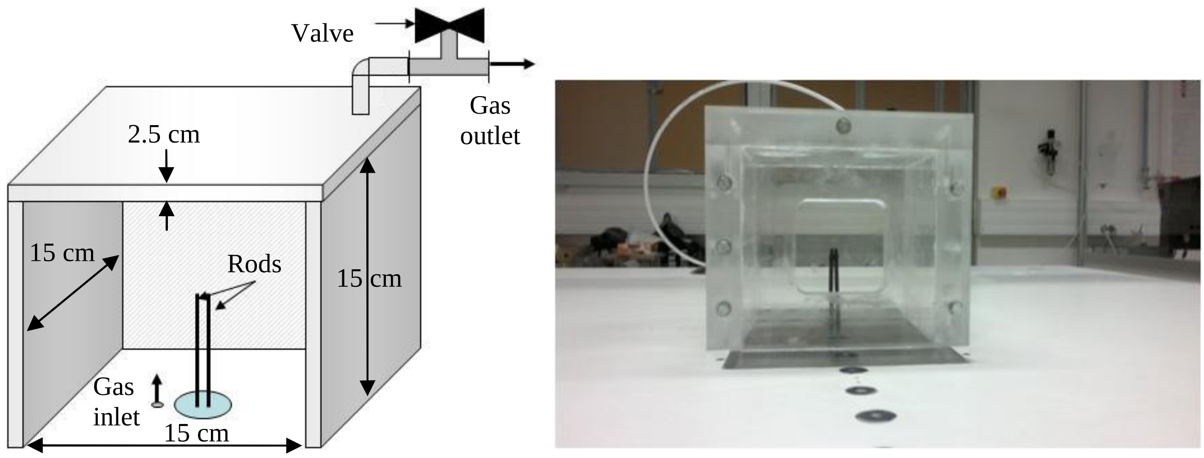

Figure 1. Front view scheme and picture of the enclosure without front wall (left) and with a vent of 25 cm^2 (right).

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, center 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. 2) and the front wall ignition corresponds to rods located at 12 mm from the wall with the vent (green enclosure in Fig. 2). The enclosure was filled with a 30% vol. hydrogen-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 not ignited immediately after the enclosure was filled. The overpressure generated by the explosion was measured by means of piezoelectric transducers PCB Piezotronics. 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 15000 fps. All pressure histories were synchronized with the video frames.

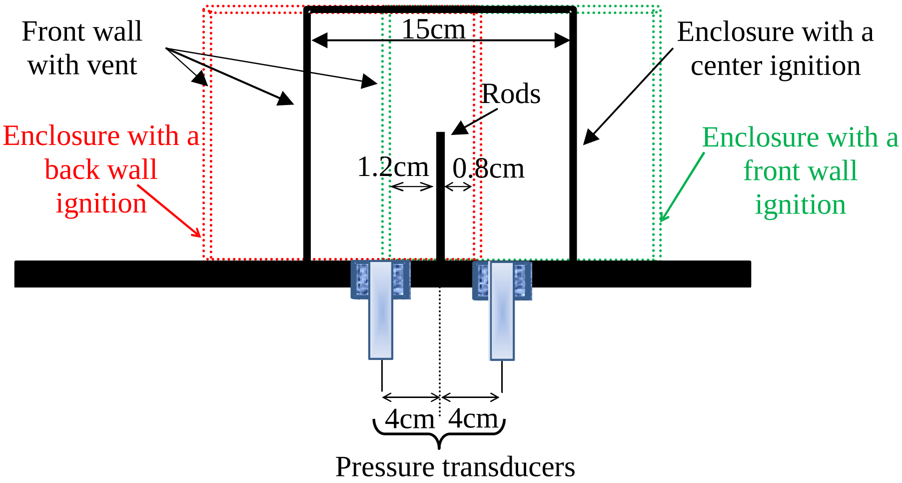

Figure 2. Location of pressure transducers and location of the cubic enclosure for front wall ignition (green), center ignition (black) and back wall ignition (red).

3.0 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 center ignition, and with one pressure transducers at 4 cm from the rods in case of front wall and back wall ignition (Fig. 2). 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. 3. A 1.5 kHz low pass filter was applied (blue) to the raw signal (black) to perform pressure peaks analysis (Fig. 3).These peaks were already identified and described by Cooper et al. [10] for a large cubic vessel (0.76 m^3) with low failure pressure relief. The first peak (P_v) is the vent cover failure pressure which was constant in our experiments (~3 kPa). The second peak (P_1) corresponds to the external explosion of the unburned fuel-air mixture which was first expelled from the enclosure then ignited by the flame coming out of the vent. The last peak P_2 occurs when the flame front reaches the wall and is controlled by resonant coupling between the flame and the acoustics modes which are generated by the geometry and the physical response of the enclosure. Recent investigations which confirmed these descriptions have been performed by Bauwens et al. [4][5] and by Chao et al. [6] with propane-air, methane-air and hydrogen-air mixtures in a 63.7 m^3 chamber and 2.42 m^3 vessel. McCann et al. [8] have observed the acoustics instabilities and the second pressure peak at small scale with methane-air mixture in a cubical vessel with sides of 38 cm for back wall and center ignition for $K_v \geq 9$. Helmholtz oscillations which could occur between the pressure peaks P_1 and P_2 [1] [2] [3] [4] were observed in our experiments only for a front wall ignition and for vent areas of 225 cm^2, 81 cm^2 and 49 cm^2, that is to say for vent coefficients $Kv \leq 4.6$. McCann et al. [8] have studied this type of oscillations with methane-air mixture in two cubical vessels with sides of 18 cm and 38 cm. The Helmholtz oscillations were only noticed for large or intermediate vent sizes, for values of K_v inferior to 4.2. In our case, it should correspond to vent sizes of 225 cm^2 ($K_v = 1$) and 81 cm^2 ($K_v = 2.8$). The smallest length of the vessel neck used by McCann was 10.5 cm whereas it is 2.5 cm in the present study. The difference could be explained by the relaxation time of the oscillations decreasing when the length of the enclosure neck decreases [5] and by the composition of the mixture which influences the period of the oscillations.

The pressure peaks P_1 and P_2 were studied according to the vent size and the ignition location, since each of these two pressure peaks can dominate. The experimental overpressure values are summarized in table 1.

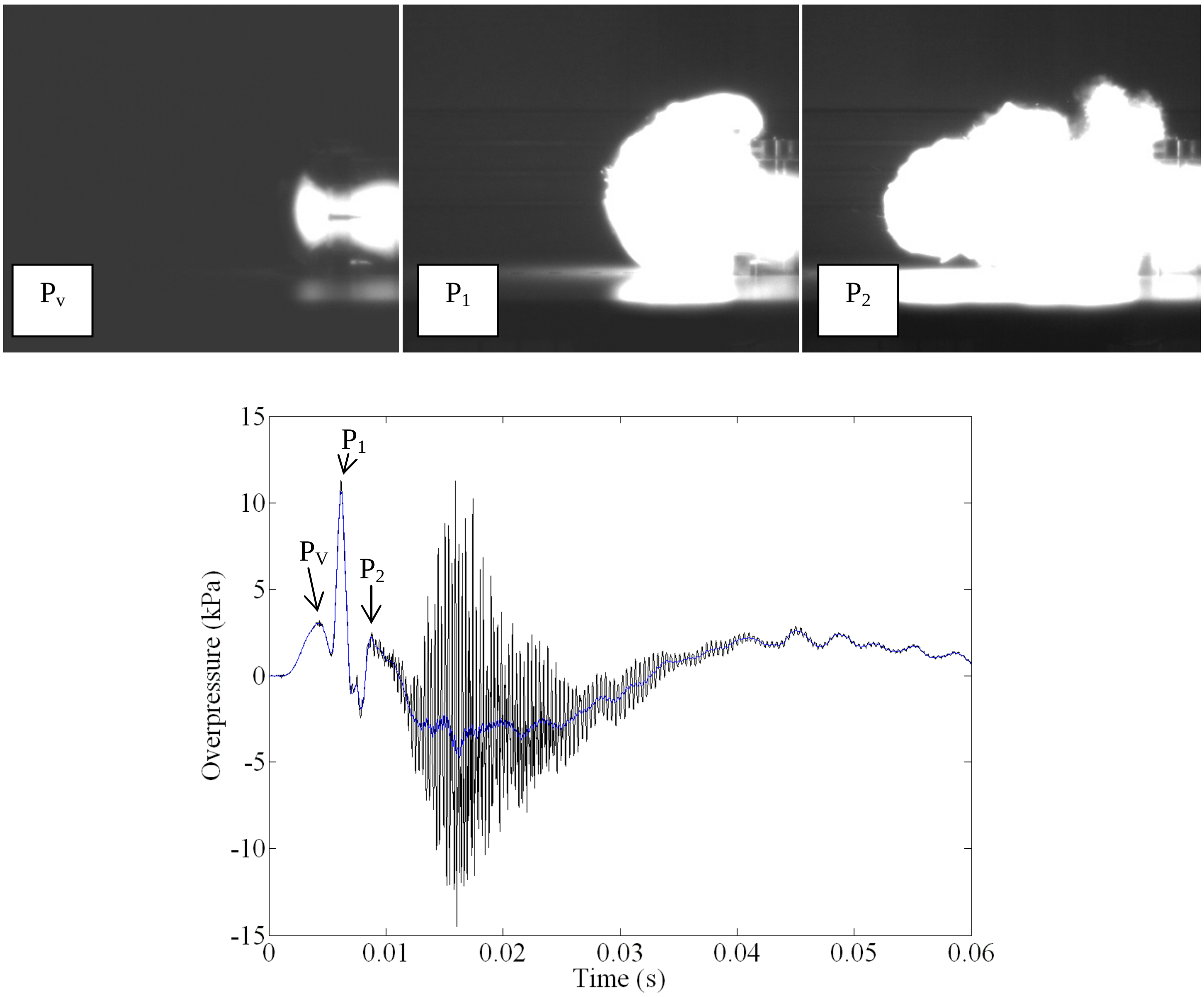

Figure 3. Pressure history of a 30% H_2-air mixture, a vent size of 81 cm^2, a center ignition, with associated video frames corresponding to the time P_v, P_1 and P_2.

It was impossible to determine ΔP_1 for center and back wall ignition with vent areas of 49 cm^2 (K_v = 4.6) or less. Indeed, the first pressure peak P_1 was included in the second pressure peak P_2 which dominates in the enclosure. The overpressure ΔP_2 was not noticed for the largest vent size (225 cm^2, K_v=1) for back wall and center wall ignition. Moreover, the second pressure peak was only noticed with vent areas of 25 cm^2 (K_v = 9) or less for a back wall ignition. For back wall ignition, small vent areas allow to trap a volume of unburned mixture enough to generate interactions between the flame and the acoustic modes in the enclosure.

As to be expected, the maximal overpressure in the enclosure increases when the vent area decreases. The maximal overpressures of 278 kPa, 196 kPa and 181 kPa were reached with a vent area of 9 cm^2 (K_v = 25) for an ignition location respectively at the center, the front wall and the back wall. The overpressure generated by the external explosion (ΔP_1) dominates for larges vent areas (225 cm^2, 81 cm^2 and 49 cm^2), in case of center and back wall ignition, where a greater volume of unburned mixture was expelled and burned outside the vessel.

On the contrary, the maximal overpressures are produced by the internal combustion (ΔP_2) for smaller vent areas (25 cm^2 and 9 cm^2) since a large amount of unburned gas was kept in the enclosure. Moreover, these smaller vent areas increase the velocity and the turbulence of the burned mixture at the vent outlet, which quickly extinguishes the external combustion (Fig. 4) resulting in a low ΔP_1 overpressure.

Table 1. Measured overpressure ΔP_1 and ΔP_2 according to the vent area and the ignition location.

Vent area (cm^2)	K_v	Center ignition		Back wall ignition		Front wall ignition
		ΔP_1 (kPa)	ΔP_2 (kPa)	ΔP_1 (kPa)	ΔP_2 (kPa)	ΔP_2 (kPa)
225	**1**	3.1	-	5.0	-	1.3
81	**2.8**	11.0	2.5	25.0	-	2.5
49	**4.6**	13.0	10.0	27.8	-	6.6
25	**9**	-	78.9	-	61.5	40.0
9	**25**	-	278.4	-	180.8	196.4

The back wall ignition leads to higher overpressures than the center ignition for vent area of 49 cm^2 or more. The back wall ignition enhances the expulsion of unburned mixture outside the vessel before it ignites and causes the maximal overpressures (ΔP_1) in the enclosure for these vent areas.

In the case of front wall ignition, the gaseous mixture burns before being thrown out of the vent to generate a burned gas jet, consequently, no pressure peak P_1 appears (Fig. 5). The front wall ignition generated the lowest overpressure values except for the smaller vent area (K_v=25).

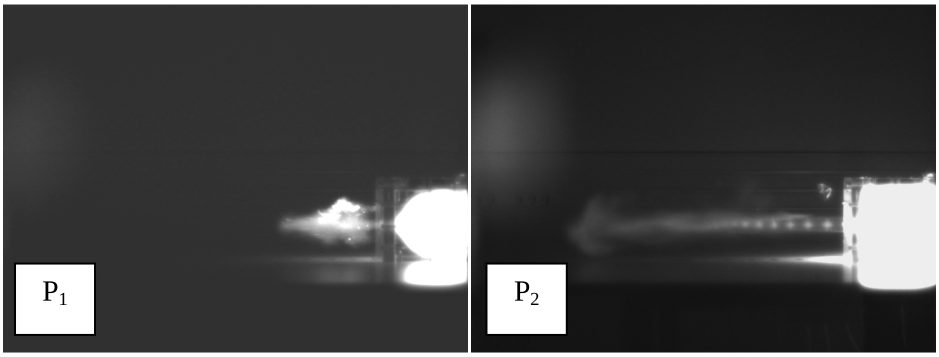

Figure 4. Video frames for a 30% H_2-air mixture, a vent size of 9 cm^2, back wall ignition, a) video frame corresponding to P_1, b) video frame corresponding to P_2 with high velocity burned gas jet.

Bradley et al. [15] have investigated available experimental data from the literature (from 1924 to 1973) about the influences of the location of the ignition source upon the maximum pressures. As observed in our experimental results, Bradley et al. have noticed that when ignition is located near the vent or near the back wall, lower maximum pressures than with central ignition were generated.
Kumar et al. [2] have studied vented explosion of 6% to 42% hydrogen-air mixtures in a 2.3 m diameter spherical vessel, with two vent sizes (rupture discs of 15 cm and 25 cm diameter) and three ignition locations. It was observed that with 20% or more hydrogen for all vent areas tested, central ignition generated the highest pressure peak and near vent ignition the lowest overpressure, but the amplitude differences were small and the effect of igniter location did not appear to be significant. The author explained this small overpressure difference to be associated with really small vent areas used in their study (K_v = 48.6 and K_v = 17.5). Experimental results in our study have shown (Table 1) that the deviation of the maximal overpressure according to the ignition location decreases in the case of the smallest vent area K_v = 25.

The evolution of the pressures peaks P_1 and P_2 seems to be in agreement with large scale experiments performed by Bauwens et al. [4][5] and by Chao et al. [6] with vent areas of 2.73 m^2 (K_v = 5.8) and 5.43 m^2 (K_v = 2.9) for methane-air and hydrogen-air and with a vent area of 0.26 m^2 (K_v = 6.9) for propane-air. The overpressure values were not compared with the hydrogen-air mixture because of the equivalence ratio which is different (18% hydrogen-air) and the scale effect. Bauwens et al. [5] have also observed that the overpressure ΔP_1 associated to the external explosion increased when ignition took place near the opposite wall of the vent, and conversely, the second pressure peak increased when the ignition location came closer to the vent.

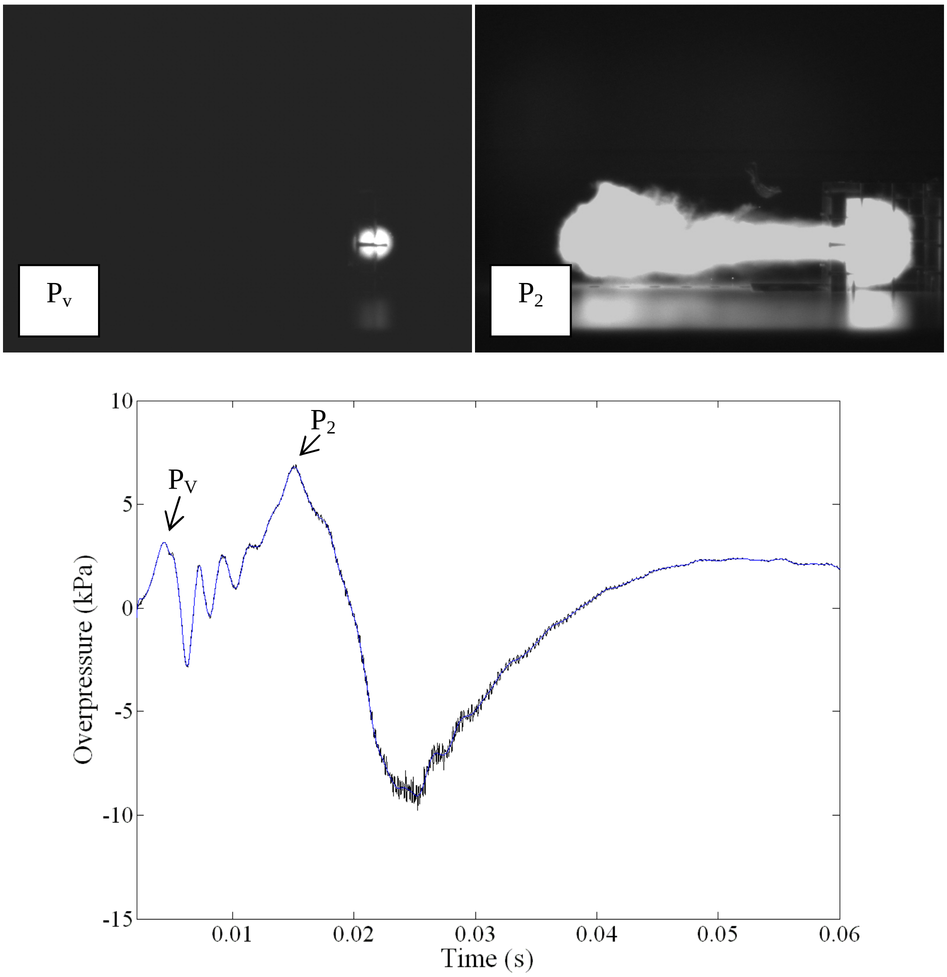

Figure 5. Pressure history of a 30% H_2-air mixture, a vent size of 49 cm^2, front wall ignition, with associated video frames corresponding to the times of P_v and P_2.

4.0 COMPARISON WITH MODELS

Two models of the literature which evaluate the overpressure in an enclosed volume during venting explosion have been compared to our experimental data, the Bauwens model [4] and the Molkov 1999 correlation [16].

4.1 Bauwens model

Bauwens et al. have published in 2010 [4], a simple physics based model which allows to estimate the magnitude of each pressure peak P_1 and P_2 (and another peak P_3 in case of obstruction). The Bauwens model takes into account the gaseous mixture composition, the enclosure size and geometry, the vent size, the ignition location and the obstacle configuration if present. A brief description of the model is given in this paper since it has been clearly described by Bauwens et al. [4] and Chao et al. [6]. The maximum overpressure in the enclosure is estimated to occur when the production of combustion products due to a flame propagating with a burning velocity, S_u, relative to the unburned mixture is equal to the venting of the reactants and products. The maximal overpressure in the enclosure therefore is controlled by the external pressure, by the maximum flame area in the enclosure and by the burning velocity. Modifications added by Bauwens [17] in 2012 have been taken into consideration to improve the model for smaller vent sizes in asymptotically approaching a constant volume explosion pressure P_{cv}, when the surface area approaches zero. A value of P_{cv} = 811.7 kPa was found for a stoichiometric hydrogen-air mixture using the computer program Gaseq [18]. The external pressure is equal to the pressure generated by the external explosion for the pressure peak P_1 and depends on a fitted constant k_T. It is assumed to be at atmospheric pressure for the pressure peak P_2. The maximal overpressure generated by the external explosion is evaluated for a flame propagating in a hemispherical cloud with a volume considered equal to the flame volume in the chamber at the time the flame exits the vent. The maximum flame area, when the flame exits the vent depends on the ignition location and the pressure peak being considered.

Bauwens et al. [19] have proposed that the initial flame velocity Su_0, controlling the pressure peak P_1, could be dependent on the Lewis number of the mixture, L_e, following the expression: $Su_0 = 0.9L_e^{-1} S_L$, with S_L the laminar flame speed. We have assumed that $S_u = S_L = 2.14$ m.s^{-1} in the present work by reason of the Lewis number which is close to 1 for a stoichiometric hydrogen-air mixture.

For the pressure peak P_2, the burning velocity increases due to flame-acoustic interactions and it is modeled with the expression: $Su = \Xi_A S_L$ where Ξ_A is a constant flame-wrinkling factor. The flame wrinkling coefficient [9] published in 2012 [9] which takes into account the effect of enclosure aspect ratio has not been considered. Indeed, the flame wrinkling factor was assumed equal to 1 in order to avoid higher overpressures generated at large scale as compared to small scale since the amplitude of the flame deformation is lower in the last case. Video frames recorded in our experiments have shown a nearly smooth flame in the enclosure, from the ignition to the time P_2 was reached.

According to this model, the maximum peak pressures in vented explosion could be modeled with two fitted constants, k_T for P_1 and Ξ_A for P_2. The constant k_T was adjusted ($k_T = 3.21$ m^{-1}) by Bauwens et al. [4] and Chao et al. [6], taking into account a vented gas composed of 90% of products and 10% of reactants. In the present work, it has been considered that this description is not easy to use practically and only those products were considered, for which it is easy to calculate properties as temperature, molar mass, calorific capacity using an equilibrium calculator software. Then, a value of $k_T = 9.26$ m^{-1} was obtained with a new fitting performed on the Bauwens et al. [4] [5] and Chao et al. [6] experiments using a linear law giving an important weight to the higher pressure experimental data. With this fitted value, a good agreement was obtained and the absolute average deviation for P_1 is 27% for the Bauwens et al. [4] [5] and Chao et al. [6] experiments.

The deviations of the model results from measured overpressures according to the vent area and the ignition location are reported in table 2 for the pressure peak P_1 and in table 3 for the pressure peak P_2. With the exception of the 225 cm^2 vent area ($K_v = 1$), the model gives rather good agreement with experimental data for the pressure peak P_1 since the mean deviation is about 36% for a center ignition, 20% and 14% respectively for back wall ignition with $K_v = 2.8$ and $K_v = 4.6$. For $K_v = 1$, which is a non common vent coefficient used for safety design, the model overpredicts the overpressure by 58% and 72% respectively for a center ignition and a back wall ignition.

Table 2. Comparison of measured overpressures ΔP_1 and Bauwens model results according to the vent area and the ignition location.

A_V (cm^2)	K_v	Center ignition			Back wall ignition		
		ΔP_1 (kPa)			ΔP_1 (kPa)		
		Measured	**Bauwens**	**Deviation (%)**	**Measured**	**Bauwens**	**Deviation (%)**
225	**1**	3.1	4.9	58.1	5.0	8.6	72.0
81	**2.8**	11.0	7.1	-35.5	25.0	19.9	-20.4
49	**4.6**	13.0	8.3	-36.1	27.8	31.6	13.7
25	**9**	-	10.1	-	-	66.3	-
9	**25**	-	13.6	-	-	269.3	-

For the pressure peak P_2, the model results are well correlated to experimental results for higher values of K_v. The maximal deviation is about 32% (back wall ignition and $K_v = 9$) and the minimal deviation is 6% (center ignition and K_v = 25) for K_v = 9 or more. For lower values of the vent coefficient, the deviation values range from 54% (front wall ignition with K_v = 1) to 124% (center ignition with K_v = 2.8).

Table 3. Comparison of measured overpressures ΔP_2 and the Bauwens model results according to the vent area and the ignition location.

A_V (cm^2)	K	Center ignition			Back wall ignition			Front wall ignition		
		ΔP_2 (kPa)			ΔP_2 (kPa)			ΔP_2 (kPa)		
		Measured	**Bauwens**	**Deviation (%)**	**Measured**	**Bauwens**	**Deviation (%)**	**Measured**	**Bauwens**	**Deviation (%)**
225	**1**	-	0.6	-	-	0.4	-	1.3	0.6	-53.9
81	**2.8**	2.5	5.6	124.0	-	3.8	-	2.5	4.4	76.0
49	**4.6**	10.0	15.7	57.0	-	10.8	-	6.6	11.8	78.8
25	**9**	78.9	58.8	-25.5	61.5	41.6	-32.4	40.0	43.4	8.5
9	**25**	278.4	295.9	6.3	180.8	235.0	30.0	196.4	237.5	20.9

4.2 Molkov 1999 universal correlation

A dimensionless correlation to deal with vent sizing for gaseous deflagration was proposed by Molkov in 1995 [14]. This correlation and more particularly some coefficients have been modified several times to validate the model with experimental data about hydrocarbon-air and hydrogen-air vented deflagration. The study was focused in a first time on the correlations published in 1999 [16], the conservative form of the correlation in 2001 [20] and the last upgraded version in 2008 [21]. The correlation consists of a first estimation of the deflagration-outflow number. This number represents the interaction between the unburned gases expelled from the vent with the burning process in the enclosure. It characterizes the level of turbulence produced during the vented deflagration. Once the deflagration-outflow number is calculated, the turbulent Bradley number which also depends on the Bradley number [15] can be estimated. Then the overpressure is evaluated from the turbulent Bradley number. The maximal overpressures were calculated with the three versions of the correlation for all vent areas tested in our experiments. For each correlation and each ignition location, the absolute deviations between modeled results and experimental measures (maximal overpressure) were calculated and were averaged for all vent areas (Table 4). Absolute deviations were considered to avoid reducing the values of average deviations since negative deviations were observed for several vent areas with all correlations except for the front wall ignition. Moreover, when accidental explosion occurs, the ignition can be located anywhere inside the enclosure. For that reason the correlation values were compared to the maximal experimental overpressures ΔP_{max}, measured with the ignition location which gave the maximal ΔP_{max} value, for each vent area (called Locations for ΔP_{max} in table 4). The correlation of Molkov 1999 gave lower absolute average deviations than other versions as can be seen in table 4.

Table 4. Absolute average deviation calculated with all vent areas, for the correlations of Molkov 1999 [16], Molkov 2001[20], Molkov 2008 [21] and for the maximal values given by Bauwens model according to the ignition location.

Ignition Location	Absolute average deviations for all vent areas (%)			
	Molkov 1999	**Molkov 2001**	**Molkov 2008**	**ΔP_{max} Bauwens**
Center	27	60	93	29
Back wall	42	92	66	33
Front Wall	133	185	361	48
Locations for ΔP_{max}	31	60	46	26

The correlation of Molkov 1999 [16] was retained to be compared to the Bauwens model since it gives better results than Molkov 2001 [20] and Molkov 2008 [21] for our experimental configuration. Consequently, the results obtained with the model of Molkov 1999 were compared to measured maximal overpressures (either ΔP_1 or ΔP_2) for all ignition locations and vent areas of this study (Table 5). The correlation does not take into account the ignition location, therefore the deviations values (Table 5) are high for the front wall ignition which generates the lowest overpressure amplitudes inside the enclosure except for $K_v = 25$.

The model agrees the best with experimental values for the central ignition which could be considered as a "neutral" location. Indeed, the absolute average deviation is 27% with all vent areas considered (Table 4). The deviation between the model values and the experimental measures decreases from -35.5% to -1.6% when the vent coefficient increases from 1 to 25, except for $K_v = 4.6$ (Table 5).

Table 5. Comparison of maximal overpressure measures ΔP_{max} and Molkov 1999 correlation results according to the vent area and the ignition location.

A_V (cm^2)	**K_v**	**Molkov (1999) ΔP_{max} (kPa)**	**Center ignition**		**Back wall ignition**		**Front wall ignition**	
			Measured ΔP_{max} (kPa)	**Deviation (%)**	**Measured ΔP_{max} (kPa)**	**Deviation (%)**	**Measured ΔP_{max} (kPa)**	**Deviation (%)**
225	**1**	2	3.1	-35.5	5.0	-60.0	1.3	53.9
81	**2.8**	9	11.0	-18.2	25.0	-64.0	2.5	260.0
49	**4.6**	22	13.0	69.2	27.8	-20.1	6.6	233.3
25	**9**	71	78.9	-10.0	61.5	15.5	40.0	77.5
9	**25**	274	278.4	-1.6	180.8	51.6	196.4	39.5

In order to compare both models to predict the maximal overpressure inside the enclosure, the maximal overpressures resulting from the Bauwens model were only retained, i.e. the maximal value between ΔP_1 and ΔP_2 was considered for each vent area. The comparison of maximal overpressures predicted by Bauwens model and Molkov 1999 correlation with maximal overpressures measured inside the enclosure, according to several vent coefficients ($K_v = 1$ to $K_v = 9$) and the three different ignition locations, is shown in Fig. 6. Data for $K_v = 25$ which gives the highest overpressure value are not reported to make easier the analysis of the graphic. The absolute average deviation was calculated with all vent areas according to the ignition location (Table 4). For a center ignition, it can be noticed that the Molkov 1999 correlation gives an absolute average deviation slightly lower than the Bauwens model, respectively 27% and 29%. For $K_v = 4.6$, the results of the Bauwens model is closer to our experimental results than the Molkov correlation. For a back wall ignition, the Bauwens model is more accurate than the correlation of Molkov 1999, the absolute average deviation being respectively 33% and 42%. As expected, the Bauwens model gives better results than Molkov 1999 for the front wall ignition.

Both models are not conservative for some configurations (negative deviations in tables 2, 3 and 5). Indeed, considering the maximal overpressure values, the Bauwens model is underpredicting for central ignition with $K_v = 9$ and for back wall ignition with $K_v = 2.8$ and $K_v = 9$. The Molkov 1999 correlation is not conservative for central ignition with $K_v = 4.6$ and for back wall ignition with $K_v = 9$ and $K_v = 25$.

When comparing both models with the maximal pressures measured for a given vent area, whatever the ignition location was (Table 4 and Fig. 7), the absolute average deviations are close between the two models (31% for the Molkov 1999 universal correlation and 26% for the Bauwens model). It can be seen in Fig. 7 that the Molkov correlation predicts the maximal overpressure better than the Bauwens model for the highest generated overpressures ($K_v = 25$). Otherwise the Bauwens model correlates a little better than Molkov 1999 correlation with experimental data concerning the maximal overpressures which can occur during an accidental ignition.

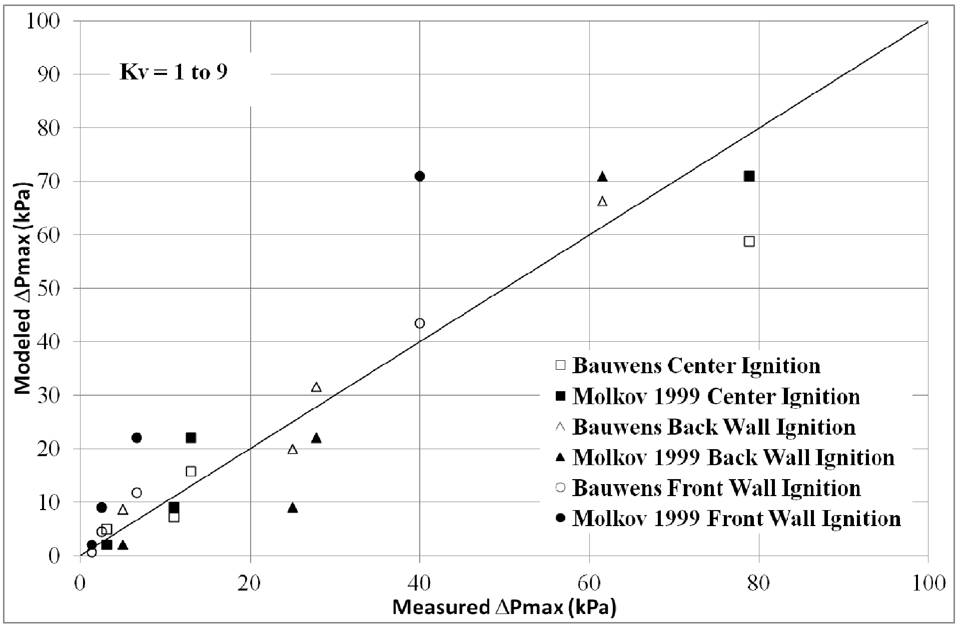

Figure 6. Comparison of maximal overpressures predicted by the Bauwens model and the Molkov 1999 model with maximal overpressures measured, for different ignition locations.

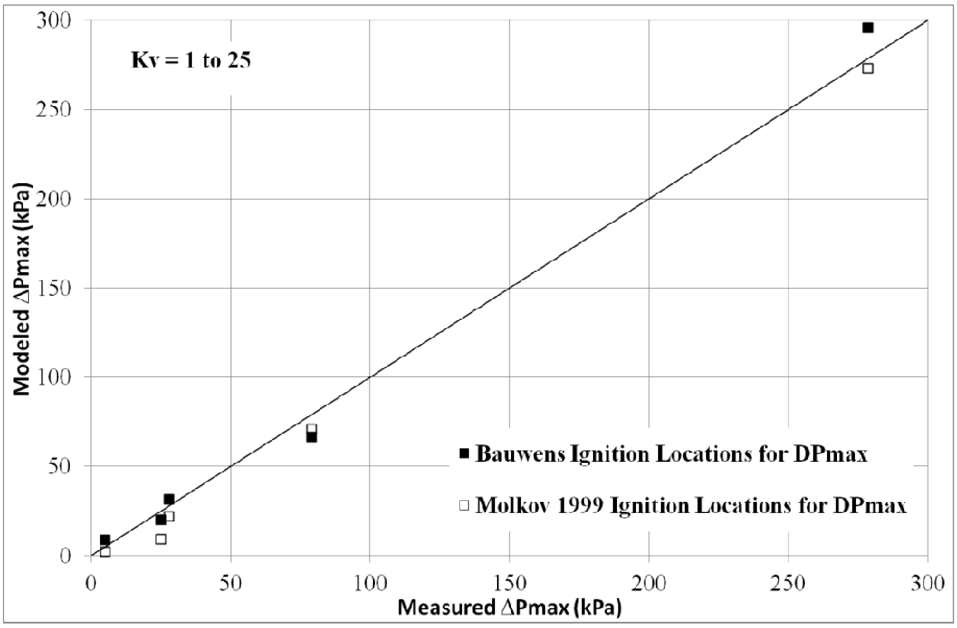

Figure 7. Comparison of maximal overpressures predicted by the Bauwens model and the Molkov 1999 model with the maximal overpressures measured for the location giving the highest overpressure.

5.0 CONCLUSION

The influence of the vent area and the ignition location on the overpressure generated inside an enclosure during a deflagration was investigated for a stoichiometric hydrogen-air mixture. Experiments were performed in a small cubic enclosure of 3375 cm^3, with three ignition locations, i.e. near vent, at the center and close to the wall opposite to the vent. The five square vents, centered on the front wall, presented a vent coefficient K_v ranging from 1 to 25. The pressure histories have shown the presence of three pressure peaks associated to the vent failure pressure (P_v), the external explosion (P_1) and the internal combustion where interaction between the flame and the acoustics modes of the enclosure occurs (P_2). The study was focused on the two pressure peaks P_1 and P_2, since each peak can be the dominating pressure in our experiments. The pressure peak generated by the external explosion was not observed in case of front wall ignition and whatever the ignition location was for small vents areas ($K_v \geq 9$). Moreover, Helmholtz oscillations, which can appear before the pressure peak produced by the internal combustion, were only noticed for a back wall ignition. As to be expected, the maximal overpressure in the enclosure increased with the vent coefficient. The front wall ignition gave the lowest overpressures for all the range of vent areas tested. The back wall ignition caused highest overpressures due to the pressure peak P_1, for larger vent areas (K_v = 1 to K_v = 4.6). For small vent areas ($K_v \geq 9$), the pressure peak P_2 was dominant and the center ignition generated the maximal overpressure values as compared to others ignition locations.

Then, two models predicting the overpressure inside an enclosure during a vented deflagration were compared to experimental values; the Bauwens model and the Molkov 1999 universal correlation. The Bauwens model is a simple physics based model which can estimate the amplitude of the pressure peaks P_1 and P_2 according the enclosure geometry, the vent area, the ignition location and the obstacles configuration if present. The Molkov 1999 correlation is a dimensionless correlation which allows predicting the maximal overpressure generated inside an enclosure during vented deflagration. For the Bauwens model, it has been assumed an initial flame velocity equal to the laminar flame velocity, considering the Lewis number to be approximately 0.9 for a stoichiometric hydrogen-air mixture. Moreover, the flame wrinkling coefficient was assumed to be 1 to avoid higher overpressures generated at large scale and a new fitting value of the constant k_T was performed on the Bauwens et al. [4] and Chao et al.[6] experiments, giving k_T=9.26 m^{-1}. With these assumptions, the Bauwens model gives rather good agreement with experimental data for the pressure peak P_1, except for K_v = 1. The same observation can be made for the pressure peak P_2, except for $K_v \leq 4.6$ for center and back wall ignition and except for $K_v \leq 9$ for front wall ignition. In order to compare both models only the maximal pressure was retained (either P_1 or P_2). Both models correlated rather well with experimental values. The Molkov 1999 correlation gave approximately similar results to the Bauwens model in case of center ignition (absolute average deviation of 27% for Molkov 1999 and 29% for Bauwens) and back wall ignition (absolute average deviation of 47% for Molkov 1999 and 33% for Bauwens). In case of front wall ignition, which gave the lowest overpressures, the Bauwens model correlated better than Molkov 1999 correlations which do not take into account the ignition location, the absolute average deviation being respectively of 48% and 133%. Finally, both models values were compared to the maximal experimental overpressures values, measured with the ignition location which gave the maximal ΔP_{max} value, for each vent area. Indeed, when accidental explosion occurs, the ignition can be located anywhere inside the enclosure. Both models gave results to experimental data, since the absolute average deviation calculated to 26% for the Bauwens model and to 31% for the Molkov 1999 correlation.

Future experiments will be performed at small scale to investigate the influence of the hydrogen concentration and the obstruction on the pressure generated during vented explosion.

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