EXPERIMENTAL STUDY OF THE EXPLOSION SEVERITY OF VENTED METHANE/HYDROGEN DEFLAGRATIONS

Torrado, D.[1], Fletcher, J.[1], Sanderson, E.[1], Tooke, A.[1], Hooker, P.[1], Isaac, T.[2], Manson-Whitton, C.[2], Lander, D.[3], Spriggs, C.[1]

[1] Health and Safety Executive (HSE), Harpur Hill, Buxton, Derbyshire, SK17 9JN

[2] Progressive Energy Ltd, Swan House, Bonds Mill, Stonehouse, Gloucestershire, GL10 3RF

[3] Dave Lander Consulting Limited, Tamworth, Staffordshire, B77 1JU

ABSTRACT

Adding hydrogen to mains natural gas has been identified as one of the main strategies to reduce CO_2 emissions in the United Kingdom. This work aims to characterise the explosion severity of 80:20 v./v. methane/hydrogen blends ('a blend') and methane vented deflagrations. The explosion severity of homogenous mixtures was measured in a 15 m^3 cubic, steel chamber, in which the relief area was provided by four windows and a door covered with polypropylene sheet. The pressure increase over time was characterised using piezo-resistive pressure transducers and the flame speed was estimated using ionisation probes installed in the walls of the enclosure. The explosion severity of both mixtures was determined for different equivalence ratios, from lean to rich mixtures.

The pressure over time presented very similar behaviour for both mixtures, comprising multiple peaks divided into three main stages: a first stage related to a spherical confined explosion until the opening of the vent, a second stage generated by increased combustion during venting, and an oscillatory peak generated by acoustic disturbances with the enclosure. A slight increase in the first stage overpressure was observed for the blend in comparison with methane regardless of the equivalence ratio, but no general trend in pressure was observed for other stages of the propagation. The effect of the blockage ratio on explosion severity was studied by adding metallic elements representing furniture in a room.

NOMENCLATURE

Symbol	Description
A_{v0}	Vent area (m^2)
A_s	Internal surface area of the enclosure (m^2)
C	Gas reactivity coefficient
C_d	Flow discharge coefficient
G_u	Unburned gas-air sonic flow mass (kg/m^2-s)
P_{max}	Maximum overpressure in confined conditions (barg)
P_{red}	Reduced Pressure (barg)
S_u	Laminar burning velocity (m/s)
ρ_u	Mass density unburnt gas-air mixture (kg/m^3)
λ	Turbulence flame enhancement factor

1.0 INTRODUCTION

In recent years, the effects of carbon dioxide production on global warming have generated international efforts to reduce the emissions of CO_2. One of the main contributors to CO_2 emissions is the burning of fossil fuels in domestic and commercial fuel supplies, especially the burning of natural gas (NG) comprised primarily of methane (CH_4). Adding hydrogen to mains natural gas has been identified as one of the main strategies to reduce CO_2 emissions in the United Kingdom. Although hydrogen presents advantages in the reduction of CO_2 emissions, a possible increase in the explosion severity of a hydrogen/methane blend could be realised if a dispersion of gas within the flammable range is ignited. For this reason, the characterisation of the explosion severity of methane/hydrogen blends is required before adding hydrogen to mains natural gas.

The maximum overpressure and flame speed of methane/hydrogen blends have been studied for small and large-scale tests previously, aiming to characterise differences with properties of natural gas explosions. Li et al., [1] measured the explosion overpressure for blended mixtures containing 0% to

100% hydrogen for lean mixtures in air, performing ignitions in a shock tube. The results showed an increase in the pressure peak for mixtures with higher concentrations of hydrogen, i.e. the peak overpressure for an equivalence ratio of 0.8 for an 80:20 v./v. methane/hydrogen was 16% higher compared to a methane explosion. In a similar experiment, Yu et al., [2] performed tests in a vented duct for blends with 25, 50, and 75% hydrogen at three equivalence ratios. The increase in the peak overpressure for 25% hydrogen in methane depended on the equivalence ratio, showing a maximum increase of 68% for an equivalence ratio of 1.

Experiments of methane/hydrogen blend explosions in medium and large-scale tests have been reported in the literature. Royle et al. [3] performed experiments in a 18 m^3 congested volume for methane, pure hydrogen, and blended mixtures containing 25%, 50%, and 75% hydrogen at equivalence ratios between 1.05 and 1.3. The peak overpressure was measured at different positions of the experimental tests, showing increases between 16% and 30% for 25%:75% methane/hydrogen blends. Lowesmith et al. [4] carried out vented explosions in an enclosure of 69 m^3 for natural gas, and blended mixtures containing 20% and 50% hydrogen at two ignition positions and with or without congestion. The maximum peak of pressure was 21% to 25% higher for the 80:20 v./v. methane/hydrogen blended mixtures compared to natural gas. Moreover, additional tests were performed in the same volume into which internal pipes were added to accelerate the flame speed. Overpressures were recorded as being up to 225% higher for the blended mixture containing 20% mol/mol hydrogen compared to pure methane [5].

Although the severity of the explosion has been studied for methane/hydrogen blends, the reported increase in comparison with methane explosions presented a considerable variability, depending mainly on the conditions of experiments. Besides, very limited information is available on vented explosion measurements for volumes and venting arrangements representing domestic properties in the UK. This work aims to characterise the explosion severity of 80:20 v./v. methane/hydrogen blends and methane vented deflagrations, inside an enclosure with a volume and venting arrangement representing a kitchen sized room in a domestic property.

2.0 METHODOLOGY

The experimental test consisted of an enclosure composed of two identical metallic rooms separated by an internal wall with a door (Figure 1). Vented explosions of 80:20 v./v. methane/hydrogen blends and methane were performed in one of the rooms, with an internal volume of 15 m^3 (2.5 x 2.5 x 2.5 m). The enclosure had an available venting area of 3.25 m^2 provided in each room by polypropylene sheet installed in the windows and door. The experiments described here were all carried out in only one room.

The flammable gas was released inside the room at a controlled pressure and volumetric hydrogen: methane ratio using a gas delivery system composed of a pressure transmitter (Bronkhorst IN-Press) and two mass flow controllers (Bronkhorst IN-Flow) in a main/slave control loop. In order to achieve homogenous mixtures, the gas was introduced to the enclosure through a perforated pipe that was placed close to the floor. The concentration inside the enclosure was measured using four thermo-conductivity sensors (Xensor Integration) calibrated for both fuels, i.e. methane and 80:20 v./v. methane/hydrogen blend. The pressure evolution over time after the ignition was measured using four piezo-resistive pressure sensors (Kulite HKL-375) installed in the walls of the enclosure with a sampling rate of 100 kHz. Pressures are reported in this work in mbar as the NFPA 68 Standard, with which the measurements are compared, reports the pressures in bar. In addition, the flame was detected using three ionisation probes installed in the walls and used for the determination of the speed of the flame front.

Six homogenous mixtures of methane and blend in air were ignited at the same fuel concentration and the maximum overpressure, the rate of pressure rise, and the flame propagation were characterised. Using the same volumetric concentration as a comparison parameter produces mixtures with different fuel/oxidant ratios. For this reason, vented explosions of blend/air mixtures at the same equivalence ratio (E.R) as the methane compositions were studied (Equation 1). Table 1 shows the six equivalence ratios studied in this work, including lean, stoichiometric, and rich mixtures.

Figure 1. Metallic enclosure for vented deflagrations

$$E.R = \frac{m_{fuel}/m_{oxidant}}{\left(m_{fuel}/m_{oxidant}\right)_{st}} \quad (1)$$

The vent area for the lean mixture was reduced because the methane deflagrations did not burst all the polypropylene sheets for 2.22 m^2 in comparison to the blend explosions.

Table 1. Volumetric fuel concentrations and equivalence ratios experimental conditions

Methane fraction (%v./v.)	Blend with the same Equivalence Ratio		Blend with the same Fuel concentration		Vent area (m^2)
	Equivalence ratio (ER)	H_2/CH_4 concentration	Equivalence ratio (ER)	H_2/CH_4 concentration	
7% CH_4	0.72	1.62% H_2 6.49% CH_4 8.11% v./v	0.60	1.4% H_2 5.6% CH_4 7.0% v./v.	1.29
8% CH_4	0.82	1.85% H_2 7.4% CH_4 9.25% v./v	0.70	1.6% H_2 6.4% CH_4 8.0% v./v.	1.75
9% CH_4	0.95	2.07% H_2 8.26% CH_4 10.33% v./v	0.79	1.80% H_2 7.2% CH_4 9.0% v./v.	1.75
9.5% CH_4	1	2.2% H_2 8.8% CH_4 11% v./v.	0.84	1.9% H_2 7.6% CH_4 9.5% v./v.	2.22
10% CH_4	1.06	2.31% H_2 9.24% CH_4 11.55% v./v	0.89	2% H_2 8% CH_4 10% v./v.	2.22
11% CH_4	1.18	2.54% H_2 10.16% CH_4 12.7% v./v.	1	2.2% H_2 8.8% CH_4 11% v./v.	2.22

3.0 RESULTS AND DISCUSSIONS

Vented explosions of homogeneous mixtures of methane/air and blend/air were performed in one of the 15 m^3 rooms as shown in Figure 2. The internal concentration was measured in four different locations inside the enclosure, and when the average intended concentration was obtained, the mixture was ignited in the centre of the room. The vent area, i.e. 2.22 m^2, was provided by two windows, and the door covered with a polypropylene sheet. The non-venting windows were blocked using metallic plates that were kept fixed by bolting a metallic frame to the interior of the box. To reduce the time difference between the bursting of the different vents, the plastic was perforated around the edges to create a similar weak point in the sheet over the windows and door.

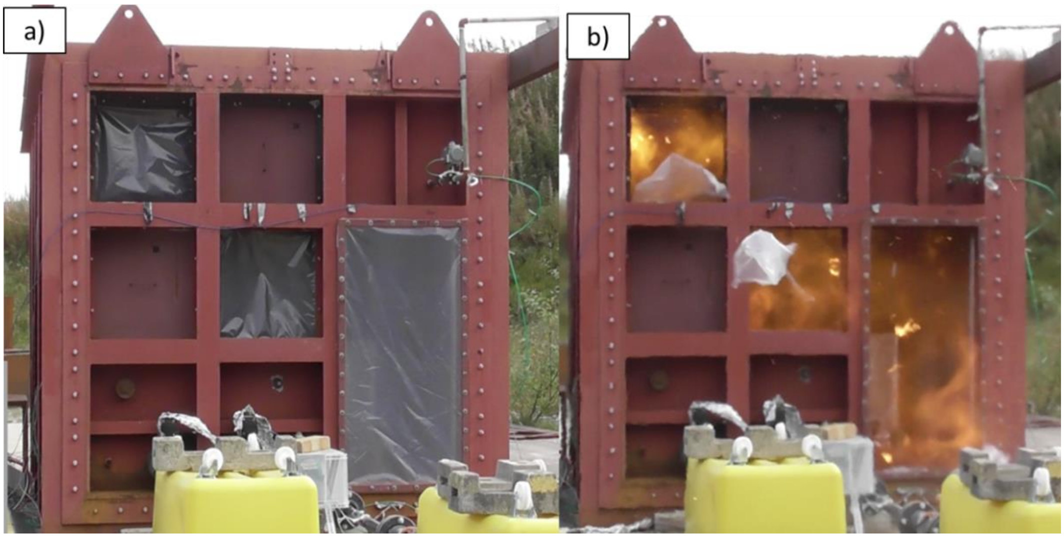

Figure 2. a) Venting arrangement for test with the blend mixture with an equivalence ratio of 1.18. b) Vented deflagration after ignition

3.1 Pressure-time evolution of methane and methane/hydrogen vented deflagrations

The pressure evolution over time and flame speed for methane and 20% hydrogen/80% methane blends were measured for the volumetric fuel concentration and equivalence ratios presented in Table 1. Figure 3 presents the pressure measurements over time for blend vented deflagrations for four equivalence ratios with a vent area of 2.2 m^3 and central ignition. The results show that multiple peaks of pressure are obtained for all the blend explosions presented studied in this work, associated with different stages of the flame propagation. The first pressure peak is related to the transition from a confined explosion, producing an increase of pressure, and a venting phase [6].

The release of gas produces a reduction in the pressure, however, due to the increase in the combustion rate as the flame continues to propagate inside the enclosure. During the established venting, more than one peak was obtained for some of the mixtures studied in this work. These peaks are associated with the stages of the vented explosion in which the flame continues to propagate, reach the vent and produce the maximum flame surface in the enclosure. Also, the external ignition of the unburnt gases released during earlier stages of the propagation may influence the internal pressure measured within the enclosure, by the generation of a back pressure over the vents and disturbing the release of gases [6-8]. Due to the complexity of the results, it is not possible to associate each peak to a specific stage of the propagation during the established venting. For this reason, from the following sections of the report, all the peaks between the confined stage (stage 1) and the oscillatory peak stage (stage 3) are grouped into the same stage and defined as established venting (stage 2). Figure 3 shows a final increase in pressure with an oscillatory behaviour after 300 milliseconds. Large scale deflagrations reported in the literature attributed the generation of the oscillatory peak behaviour to flame instabilities [6,9], which under specific conditions, are generated from the interaction between combustion of remaining gases after venting and acoustic disturbances generated by fluctuations in the heat release. If the acoustic disturbances occur at the same frequency as the flame release, strong pressure oscillations are generated [6, 9]. The resonance between periodic heat release and pressure oscillations is defined as Rayleigh's criteria. Some studies of large-scale vented deflagrations have attributed this oscillatory behaviour to instabilities generated by a less dense gas being accelerated to a denser unburned mixture (Taylor instabilities) [10, 11]. Nevertheless, the high frequency oscillations could also have been generated by the movement and vibrations of the enclosure producing noise on the signal measured by the pressure transducers. Although this effect on the measured pressures cannot be discarded, the magnitude of the positive impulse of the last peak together with the flame being detected on the wall at this stage (Figure 3) suggest that the flame instabilities produce the final increase of pressure as described in the literature [6, 9]. For the results presented in Figure 3, no considerable changes were obtained in the first peak overpressure for equivalence ratio above 0.84, i.e. 40 to 44 mbar g (4 to 4.4 kPa). However, the rate of pressure rise increases for the first peak, presenting the greatest increase for the equivalence ratio of 1.06. Regarding the last stage of the propagation, the oscillatory peak was presented for all the equivalence ratios shown in Figure 3. The rate of pressure rise and maximum pressure for this peak was the greatest for an equivalence ratio of 0.89, nevertheless, the maximum overpressure obtained for an equivalence ratio of 1.06 was very similar, i.e. 121 mbar g (12.1 kPa) compared to 132 mbar g (13.2 kPa).

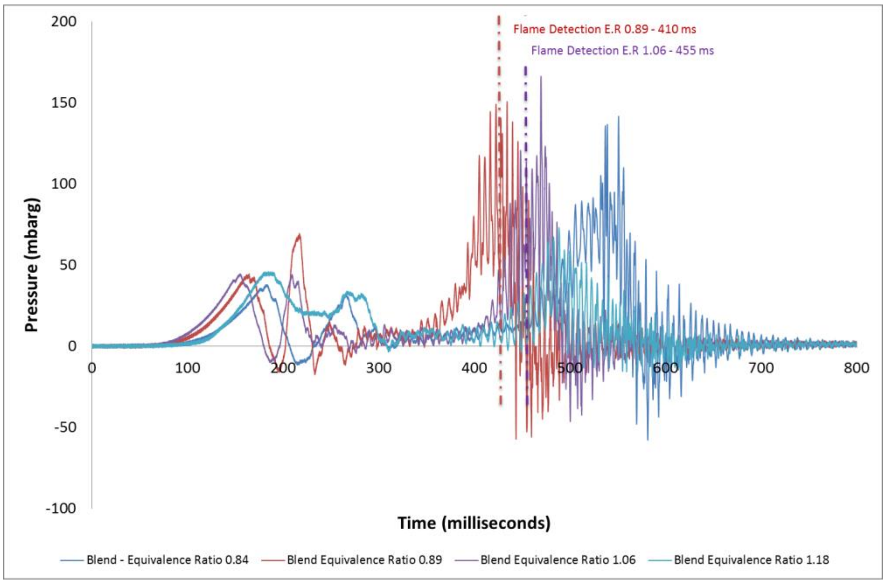

Figure 3. Pressure-time results for blend vented explosions at different equivalence ratios

The pressure-time profiles at 7% fuel volumetric concentration in air for methane and blend are presented in Figure 4. The pressure evolution presents very similar trends for both gases at the same fuel concentration, comprising multiple peaks associated with different stages of the flame propagation.

The overpressures measured for the methane vented explosion are higher in comparison to blend mixtures at the same fuel concentration and the same equivalence ratio, especially for the first peak. Because the pressure profile results suggest a slightly higher rate of pressure rise for the blend; the higher overpressures recorded for methane do not seem related to higher methane's reactivity. This result can be explained because the methane explosion generates a low rate of pressure rise that would require more time to completely remove the venting and reach a full flow out of gas, generating a less efficient relief of pressure than explosions of the blend at the same conditions. The pressure-time profile shown in Figure 4 for both methane and blend at a concentration of 7% v./v. of fuel did not present the generation of rapid pressure oscillations associated with flame instabilities. It has been reported in the literature that the amplitude of the oscillatory peaks is dependent on the burning velocity [6], which would explain that these mixtures with low burning velocities do not generate the instabilities to produce the oscillatory peak during the vented explosion. The pressure measurements of the blend vented explosion at the same equivalence ratio of a 7% v./v. methane/air mixture (i.e. equivalence ratio of E.R 0.72) were recorded (Figure 4). The pressure seems to rise faster after ignition and the time required to reach each peak is lower for the blend, suggesting that the combustion rate of the blend vented explosion at an equivalence ratio of 0.72 seems considerably greater than methane at the same ratio, even if the maximum overpressure obtained was higher for methane. In addition, the blend at this equivalence ratio presents an oscillatory stage at the end of the propagation, associated with flame instabilities generated by the interaction between the flame and the walls of the enclosure [6-8].

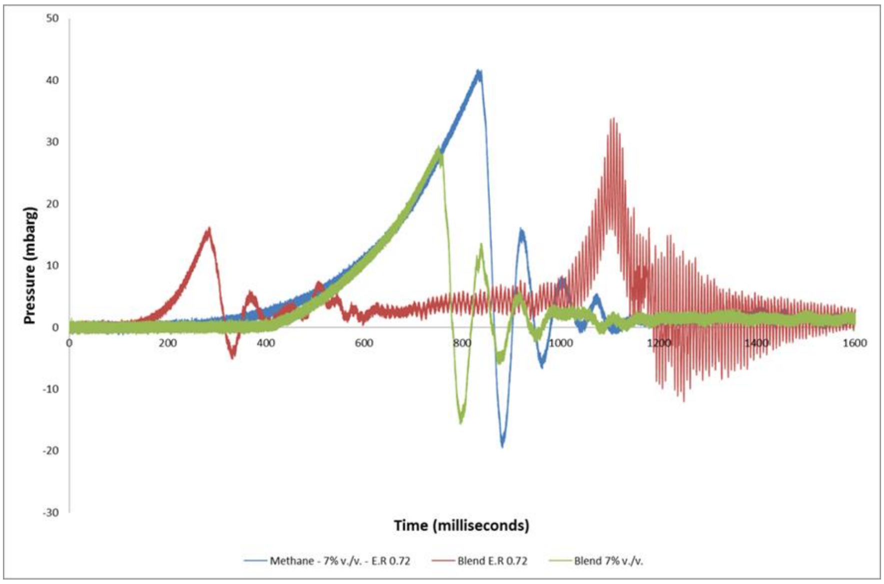

Figure 4. Pressure evolution for 7% v./v. methane. (E.R 0.72), blend with 7% v./v. fuel concentration and blend with 0.72 E.R.

Figure 5 shows the pressure measurements for methane and blend deflagrations at 9% v./v. fuel concentration. In contrast with leaner concentrations studied in this work (Figure 4), the pressure trend for the blend at 9% v./v. presents a different behaviour in comparison with methane at the same volumetric concentration. Although the first peak for both fuels represents the confined explosion stage until the full outflow of gas is established, the pressure measurement for the blend/air mixture shows only one peak for the established venting stage, while three peaks are obtained for the methane explosion. This result may be explained by the increased rate of pressure rise for the blend at the same concentration, reducing the difference in the bursting time of each of the windows and door, and therefore, improving the release of gas outside the enclosure. In contrast, for the methane explosion, the difference in the time in which each vent burst may explain the generation of multiple peaks.

The third peak of the blend explosion at 9% v./v., shows that an overpressure of an average of 97.5 mbarg (9.75 kPa) was obtained for the oscillatory stage associated with flame instabilities. However, the oscillatory pressure peak was not evidenced for the methane explosion at 9% v./v., in which the third stage has a long duration characteristic to the continuous propagation of the flame until reaching the maximum flame surface [6]. The pressure measurements of the blend vented explosion at the same equivalence ratio as a 9% v./v. methane/air mixture (i.e. equivalence ratio of E.R 0.95) were measured and are shown as well in Figure 4. The pressure rises considerably faster after ignition and the time to reach each peak is lower for the blend at the same equivalence ratio than for methane. Although the rate of pressure rise of the first peak is greater for a blend deflagration at E.R = 0.95 in comparison to E.R = 0.79 (9% v./v. fuel), the pressure peaks are greater for the leaner mixture. The maximum overpressure for a blend explosion at E.R = 0.79 (9% v./v. fuel) was as well higher than the one obtained for the blend at a E.R = 0.95. This result did not follow the expected trend, i.e. a higher overpressure for E.R = 0.95, but it may be explained due to the high variability expected in a phase of the propagation dominated mainly by the turbulence and instabilities of the flame.

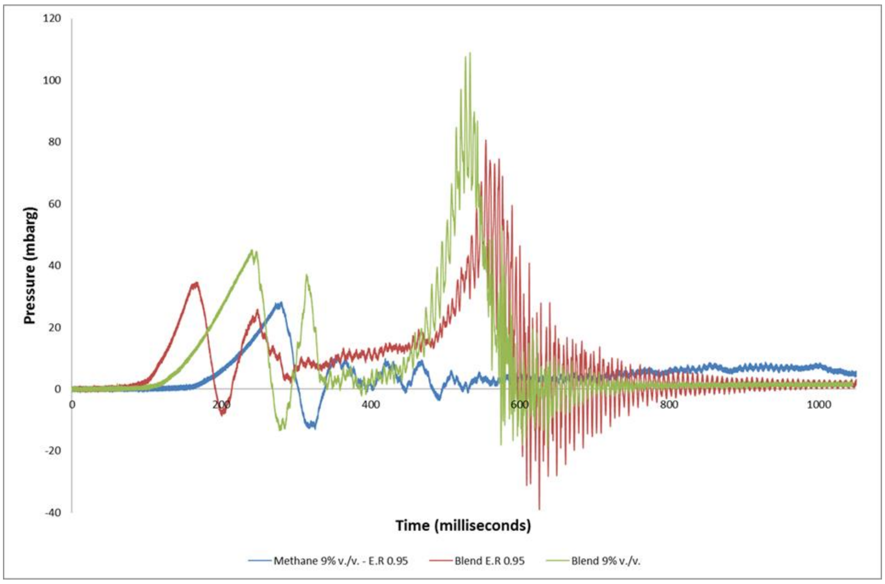

Figure 5. Pressure evolution for 9% v./v. methane (E.R 0.95), blend with 9% v./v. fuel concentration and blend with 0.95 E.R.

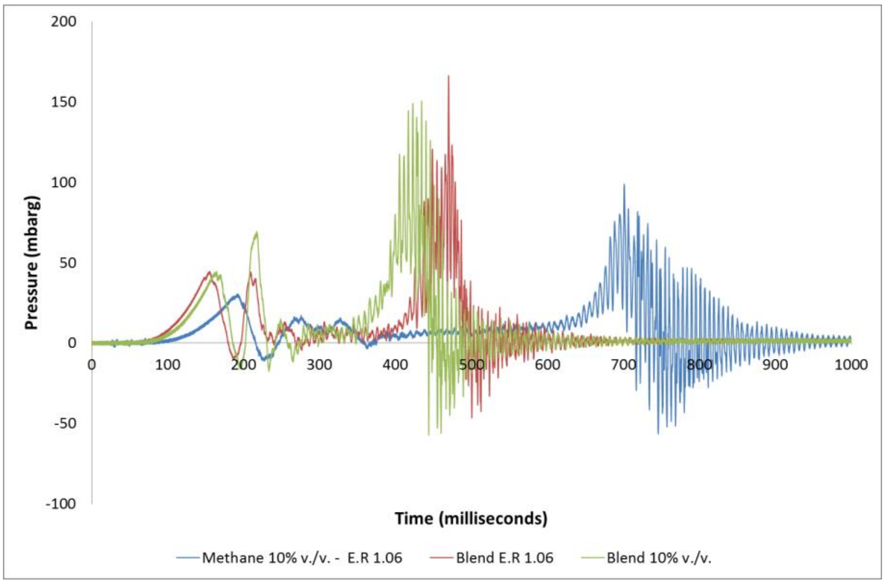

Figure 6. Pressure evolution for 10% v./v. methane (E.R 1.06), blend with 10% v./v. fuel concentration and blend with 1.06 E.R.

Figure 6 presents the pressure-time measurements for methane and blend deflagrations at 10% v./v. fuel concentration. The pressure evolution measured for both fuels at the same concentration shows a very similar trend, composed of three described by different stages of the propagation. For a 10% v./v. methane vented explosion, the pressure increases up to 30 mbarg (3 kPa) during a confined stage until a reduction is generated by the venting (stage 1). Once the venting has been established (stage 2), two peaks of similar pressure, i.e. 15 mbarg (1.5 kPa), are obtained due to the continuous increase on the flame surface. It has been evidenced that the long-duration stage is related to a gradual increase of pressure until an oscillatory peak increase is measured, related to the generation of instabilities when the flame interacts with the walls of the enclosure. Similar behaviours are described in the literature [6, 9], attributing this stage to a transition in which the flame reaches the maximum area and then interacts with the enclosure, producing the oscillatory peak.

Regarding the blend ignition at 10% v./v. fuel concentration, an increase in overpressure for the stage 1 and 2 has been measured in comparison to the methane deflagration at the same concentration, e.g. 45% increase for the confined stage. For the established venting stage, two peaks are also obtained; nevertheless, the increase of combustion rate seems to produce a higher overpressure than that obtained for the first stage of the propagation. Furthermore, the highest overpressure during the blend vented explosion at this concentration was obtained for the flame instabilities stage, producing pressures up to 120 mbarg (12 kPa). The pressure trend of the blend (Figure 6) suggests that the flame interacts with the wall before the maximum surface can be obtained [6]. Regarding a blend ignition at an equivalence ratio equal to 1.06, the pressure profile follows a similar behaviour and overpressures than the blend explosion at an equivalence ratio of 0.89 (10% v./v. fuel concentration). Although the results presented in this work are focused on possible changes on the maximum overpressure, the structural damages to a building are dependent on the coupled effect of the overpressure and impulse generated by the deflagration. The detailed analysis on the changes in impulse for blend and methane will be covered in a separate publication.

3.3 Flame speed measurements empty room

The flame speed (S_f) is defined as the velocity in which the flame front moves through a flammable mixture measured from a fixed position. In this work, the flame speed was measured in three locations (i.e. in the wall) using the ionisation probes for a flame moving from the ignition point towards the walls/vents, from which the time of detection was determined, and the speed estimated using the distance of each probe from the ignition source. Table 2 presents the average flame speed measured for the three positions in the enclosure for methane and blend at different equivalence ratios.

Table 2. Flame speed of homogeneous mixtures of methane and blend at different equivalence ratios.

Equivalence Ratio (Fuel concentration)	Methane		Blend same Equivalence Ratio		Relative Change	Blend same Fuel concentration		Relative Change
	Average Flame Speed (cm/s)	Standard deviation (cm/s)	Average Flame Speed (cm/s)	Standard deviation (cm/s)		Average Flame Speed (cm/s)	Standard deviation (cm/s)	
0.72 (7% v./v.)	86.70	15.71	126.39	6.91	45%	93.46	16.78	8%
0.82 (8% v./v.)	108.38	12.59	172.34	8.37	58%	122.97	14.94	13%
1.06 (10% v./v.)	206.30	11.76	318.68	18.52	54%	336.9	11.35	63%
1.18 (11% v./v.)	305.16	65.68	340.46	65.26	12%	280.34	3.38	-8%

The measured flame speed for the blend is always higher than the one for methane when compared at the same equivalence ratio. This result is in agreement with the greater rate of pressure rise evidenced for the blend in section 3.1, suggesting that the combustion rate of blend mixtures in the air was higher than those of methane at the same equivalence ratio. The increase of flame speed is within the range of 45% to 60%, except for the equivalence ratio 1.18. Regarding the equivalence ratio of 1.18, the relative difference is of 12% only, but a considerable variability of the detected flame speed was evidenced in comparison with the other equivalence ratios studied in this work. The burning velocity of the vented explosions was not reported because the detection of the flame was performed in the walls of the structure and therefore the flame speed was already affected at that point by the effect of the venting and turbulence on the combustion rate, heat exchange, and fluid dynamics.

3.4 Effect of blockage ratio on the pressure-time measurements

In domestic properties, it is very unlikely to find a room without any furniture inside, and in case of a gas explosion, the blockage ratio generated by the furniture may affect the explosion severity of the deflagration. This section aims to analyse the effect of a blockage ratio of 22%, i.e. provided by two metallic elements representing furniture (Table 3), on the pressure-time evolution and flame speed of methane and blend vented deflagrations. The element representing the cooker was placed against the internal wall just below the venting windows, while the metallic piece representing the refrigerator was placed in the corner between the internal wall and the wall of the box (opposite to the venting door).

Table 3 Metallic furniture and blockage ratio.

Metallic furniture	Width (mm)	Depth (mm)	Height (mm)	Blockage ratio (%surface)
Cooker	600	600	900	7%
Refrigerator	700	700	1800	15%

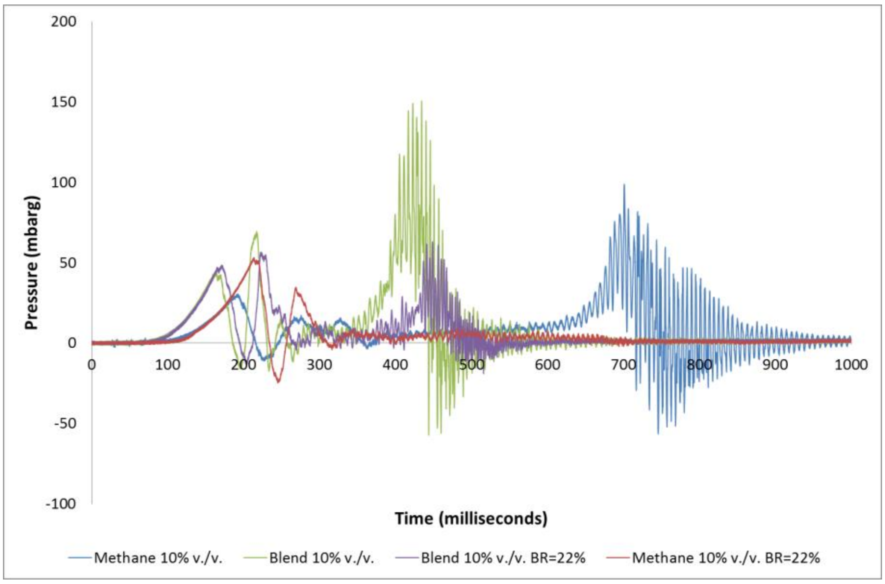

Figure 7. Pressure evolution for 10% v./v. methane and 10% v./v. blend homogeneous mixtures in the empty and obstructed room with a blockage ratio (BR) of 22%

Figure 7 presents pressure-time measurements for methane and blend deflagrations at 10% v./v. fuel concentration in a room with a blockage ratio of 22%. The traces obtained for an empty room at the same conditions are included in the same figure. The pressure measurements for methane show a considerable increase in the peak overpressure associated with the confined propagation and established venting (stages 1 and 2). A similar rate of pressure rise during the spherical propagation of the flame is obtained, suggesting a very little effect of the obstacles in the early stage of the explosion. Nevertheless, the addition of the two metallic furniture pieces generated a significant reduction in the maximum pressure of the oscillatory peak i.e. a reduction of 90 % on the last peak´s overpressure was obtained for the vented deflagration of methane in the room with obstructions. The effect of furniture on the stage associated with flame instabilities is in agreement with the results reported in the literature [6]. This result may be explained by a reduction in the available internal area that can resonate with the flame during the last stage of the propagation.

The addition of two pieces of furniture seems to have a different effect on the 10% v./v. blend deflagration in comparison to the results previously described for methane at the same concentration. Even if a slight increase in overpressure is obtained for the first stage of the propagation (i.e. 11% of increase for the initial peak compared to the results in the empty room), the results suggest that the addition of furniture increasing the blockage ratio to 22% does not have a considerable effect on the explosion severity during the stages associated with the confined propagation and established venting (stages 1 and 2). Nevertheless, the addition of just two pieces of furniture has a considerable effect on the acoustic disturbances during the stages. As evidenced by methane, the rate of pressure rise is not considerably affected during the first stage of the propagation.

Table 4 presents the average flame speed measured in the enclosure for methane and blend at different equivalence ratios for a blockage ratio of 22%. The results show that the front flame for the blend propagates faster than methane, as was reported for the empty room. The average flame speed increase ranges between 25 and 95 %, however there is no clear pattern of the effect of the equivalence ratio on the flame speed at this blockage ratio. The measurement standard deviations shown in table 4 indicate that the addition of furniture increases the variability of the estimated flame speed at each location.

Table 4. Flame speed of homogeneous mixtures of methane and blend at different equivalence ratios for a blockage ratio in the room of 22%

Blockage ratio 22%					
Equivalence Ratio	Methane		Blend		Relative Change
	Average Flame Speed (cm/s)	Standard deviation (cm/s)	Average Flame Speed (cm/s)	Standard deviation (cm/s)	
0.82	267.73	29.95	380.05	183.94	41%
1.06	240.47	31.36	302.81	46.08	25%
1.18	299.23	28.21	582.36	150.54	95%

3.5 Comparison between experimental results and overpressures predictions using the standard NFPA 68:2013

The Standard on Explosion Protection by Deflagration Venting – NFPA 68: 2013 [12] provides design methods for venting of combustion gases from deflagration of gases, mists mixtures, dust, or hybrid mixtures in industrial vessels or pipework. This standard allows a conservative estimation of the vent area A_{v0}, required to protect an enclosure from a deflagration. When $P_{red} \leq 0.5\ bar$, the minimum vent area shall be determined following Equations 2 and 3

$$A_{v0} = \frac{A_S C}{\sqrt{P_{red}}} \tag{2}$$

$$C = \frac{S_u \rho_u \lambda}{2 G_u C_d}\left[\left(\frac{P_{max}+1}{P_0+1}\right)^{1/\gamma_b} - 1\right](P_0+1)^{1/2} \tag{3}$$

The estimation of A_{v0} is based on the determination of the gas reactivity coefficient C, which is dependent on the laminar burning velocity S_u, the flow discharge coefficient C_d, the maximum overpressure in confined conditions P_{max} and the turbulence flame enhancement factor λ [12]. When $P_{red} > 0.5\ bar$, the required vent area A_{v0} shall be calculated following Equations 4 and 5.

$$A_{v0} = A_S \frac{\left[1 - \left(\frac{P_{red}+1}{P_{max}+1}\right)^{1/\gamma_b}\right]}{\left[\left(\frac{P_{red}+1}{P_{max}+1}\right)^{1/\gamma_b} - \delta\right]} \frac{S_u \rho_u}{G_u} \frac{\lambda}{C_d} \tag{4}$$

$$\delta = \frac{\left[\left(\frac{P_{stat}+1}{P_0+1}\right)^{1/\gamma_b} - 1\right]}{\left[\left(\frac{P_{max}+1}{P_0+1}\right)^{1/\gamma_b} - 1\right]} \tag{5}$$

The reduced pressure was estimated for the experimental conditions presented in Table 1 for methane and blend, using the laminar burning velocities reported by Huang et al. [13]. Table 5 presents the maximum overpressure measurements for homogeneous mixtures of methane and blend in the empty room and the estimations using the standard NFPA 68:2013 [12]. The maximum pressure peaks were estimated from smoothed traces, by detecting the maximum peak value and averaging within 200 points (sampling rate 100 kHz) to consider the effect of oscillations (especially for the last stage of the propagation). The results show that the maximum overpressures measured for the vented deflagrations are considerable below the pressures calculated using the NFPA 68:2013, i.e. 500 mbarg (50 kPa) for stoichiometric conditions. Due to the limited data, conservative values of the maximum overpressure in confined conditions (P_{max}) and the laminar burning velocity were used for the estimation of the reduced pressure for 20% hydrogen/80% methane blends. Furthermore, the consideration of the turbulence, using the λ factor, is performed in the standard by taking to account the fluid dynamics associated with the flame propagation (Re_f) and the fluid dynamics of the outflow (Re_v) [12]. The empirical factors and conservative burning velocity used for the estimation of those two contributions may generate a considerable overestimation of the turbulence generated on the empty room with a central ignition. Although the standard aims to provide elements for the conservative sizing of vent devices to protect industrial equipment and pipework, the experimental results for the specific conditions of this work suggest that considerably bigger vents will be obtained with the standard in comparison with those actually required to maintain the reduced pressure to a specific level. However, the difference between the experimental results and the standard estimations might be considerably reduced with more data on the explosion severity of blend mixtures in congested conditions. In addition, empirical correlations developed by Molkov et al [14, 15] and Sinha et al [16] have been used for the prediction of the maximum overpressure of blend, results that will be presented in a separate publication.

Table 5. Comparison between maximum pressure peak obtained for three different equivalence ratios and estimations obtained using NFPA 68:2013

Equivalence Ratio.	Methane Max. Pressure Peak mbarg (kPa)	Blend Max. Pressure Peak mbarg (kPa)	NFPA 68:2013 Methane Peak mbarg (kPa)	NFPA 68:2013 Blend Peak mbarg (kPa)
0.8	24.4 (2.44)	32.04 (3.2)	200 (20)	285 (28.5)
1	34.6 (3.46)	110 (11.0)	300 (30)	500 (50)
1.18	57.8 (5.78)	64.7 (6.47)	235 (23.5)	375 (37.5)

4.0 CONCLUSIONS

This work studies the explosion severity of methane and 20% hydrogen/80% methane blends vented deflagrations in a 15 m^3 room. The vented deflagrations for both fuels presented multiple peaks in the pressure-time measurements, divided into three main stages: a first stage related to a spherical confined explosion until the opening of the vent, a second stage generated by an increased combustion during venting, and an oscillatory peak generated by acoustic disturbances with the enclosure. For the blend mixtures, the pressure seems to rise faster after ignition and the time required to reach each peak pressure is lower in comparison to methane deflagrations at the same equivalence ratio or fuel concentration. The oscillatory peak, associated with flame instabilities during propagation, was observed for concentrations above 7% v./v. of the blend, while this peak was only observed at higher methane concentrations (above 9.5% v./v. fuel concentration).

The pressure evolution over time obtained for tests with a blockage ratio of 22%, i.e. by placing two metallic elements inside, shows that for methane, the overpressure of the peaks during the confined and established venting increases in comparison with methane deflagrations on an empty room. The addition of two metallic furniture pieces results in a significant reduction on the maximum overpressure for the oscillatory peak. For blend deflagrations, the overpressure obtained during the initial stages was not modified, while the oscillatory peak was considerably attenuated.

5.0 ACKNOWLEDGEMENT

The hydrogen measurement instrumentation was provided by the Sensor Laboratory at the National Renewable Energy Laboratory (NREL), with funding from the DOE Fuel Cell Technology Office. NREL Sensor Laboratory personnel (William Buttner and Matthew Post) provided technical support on the calibration and use of the thermos-conductivity sensors. This paper's contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

REFERENCES

1. Li, T., Hampp, F. and Lindstedt, R. P. (2015). Turbulent explosions in H_2 enriched CO and CH4 mixtures. Proceedings of the 25th ICDERS, Leeds.
2. Yu, M., Zheng, K., Zheng, L., Chu, T. and Guo, P. (2015). Effects of hydrogen addition on propagation characteristics of premixed methane/air flames. Journal of Loss Prevention in the Process Industries, 34, 1-9
3. Royle, M., Shirvill, L. C. and Roberts, T. A. (2007). Vapour cloud explosions from the ignition of methane/hydrogen/air mixtures in a congested region. In International conference on hydrogen safety, September 2007, San Sebastian.
4. Lowesmith, B. J., Mumby, C., Hankinson, G. and Puttock, J. S. (2011a). Vented confined explosions involving methane/hydrogen mixtures. International Journal of Hydrogen Energy, 36(3), 2337-2343.
5. Lowesmith, B. J., Hankinson, G. and Johnson, D. M. (2011b). Vapour cloud explosions in a long congested region involving methane/hydrogen mixtures. Process Safety and Environmental Protection, 89(4), 234-247.
6. Harris, J. (1983). The Investigation and Control of Gas Explosions in Buildings and Heating Plant, British Gas
7. Gadner, D. and Hulme, G. (1995). A survey of current predictive methods for explosion hazard assessments in the UK offshore industry, United Kingdom
8. Cooper, M.G., Fairweather, M. and Tite, J.P. (1986). On the mechanisms of pressure generation in vented explosions, Combustion and Flame, 65: 1-14.
9. Tamanini, F. (1992). Turbulent vented gas explosions with and without acoustically-induced instabilities, Twenty-Fourth Symposium (International) on Combustion
10. Bauwens, C.R., Chaffee, J. and Dorofeev, S. 2008. Experimental and Numerical Study of Methane-air Deflagrations in a Vented Enclosure, International association for fire safety science (FM Global)
11. Tomlin, G., Johnson, D.M., Cronin, P., Phylaktou, H.N. and Andrews, G.E. (2015). The effect of vent size and congestion in large scale vented natural gas/air explosions, Journal of Loss Prevention in the Process Industries 35: 169 – 181.
12. NFPA 68, Standard on Explosion Protection by Deflagration Venting, National Fire Protection Association, Edition 2013.
13. Huang, Z., Zhang, Y., Zeng, A., Wang, Q. and Jiang, D. (2006). Measurements of laminar burning velocities for natural gas–hydrogen–air mixtures. Combustion Flame 146:302–311.
14. Molkov, V, Bragin, M, 2015, Hydrogen–air deflagrations: Vent sizing correlation for low-strength equipment and buildings, International Journal of Hydrogen Energy, 40: 1256 – 1266.

15. Molkov, V, Dobashi, R, Suzuki, M, Hirano, T, 2000, Venting of deflagrations: hydrocarbon-air and hydrogen-air systems, Journal of Loss Prevention in the Process Industries 13: 397 – 409.
16. Sinha, A, Wen, J, 2019, A simple model for calculating peak pressure in vented explosions of hydrogen and hydrocarbons, International Journal of Hydrogen Energy, 44: 22719 – 22732.