Influence of Congestion on Vented Hydrogen Deflagrations in 20-foot ISO Containers: Homogeneous Fuel-Air Mixtures

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1 Introduction

Further progress in the field of hydrogen safety is a prerequisite for widespread acceptance and use of hydrogen as an energy carrier in society. Fires and explosions represent a significant hazard for hydrogen installations, and specific measures are generally required for reducing the risk to an acceptable level [1]. It is common practice in industry to install electrolysers, refuelling stations, fuel cell backup systems and other equipment for hydrogen energy applications in containers or smaller enclosures, and explosion venting is a frequently used measure for reducing the consequences of hydrogen deflagrations in confined systems. Whereas most enclosures used for hydrogen applications in industry are inherently congested, the empirical correlations in international standards for design of venting devices, such as EN 14994 [2] and NFPS 68 [3], originate from explosion experiments performed with empty vessels. This situation motivated the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) call for proposal FCH-04.3-2014: 'Pre-normative research on vented deflagrations in containers and enclosures for hydrogen energy applications'. In 2015, FCH JU granted funding to the project 'Improving Hydrogen Safety for Energy Applications through pre-normative research on vented deflagrations', or HySEA (www.hysea.eu). The HySEA project is scheduled to run from September 2015 to August 2018. The members of the HySEA consortium are Gexcon AS (coordinator), University of Warwick, University of Pisa, Fike Europe B.v.b.a., Impetus Afea AS and Hefei University of Technology. The research activities in the project are organized in three work packages (WPs):

- WP1: Engineering models and standards
- WP2: Experimental campaigns
- WP3: Advanced modelling

WP2 includes two experimental studies: University of Pisa investigates hydrogen explosions in smaller enclosures and Gexcon conducts full-scale explosion experiments in 20-foot ISO containers. Each study consists of two separate campaigns: explosions in initially quiescent and homogeneous gas clouds, and explosions in initially turbulent and inhomogeneous clouds. In addition, Hefei University of Technology will conduct a series of experiments in 40-foot ISO containers. This paper presents results from the first part of the experimental campaign conducted by Gexcon, with homogeneous mixtures. The output from WP2 is important input to WP1, where the aim is to develop and validate engineering models suitable for standards, as well as to the work on computational fluid dynamics (CFD) and finite element (FE) methods in WP3.

2 Previous work

Vented hydrogen deflagrations have been extensively studied in the past, but primarily in empty enclosures. The experiments conducted by Sommersel *et al.* in a 20-foot ISO container with varying degrees of congestion [4-5], resembles the work presented here. However, these experiments involved ignition of transient releases, and is therefore more relevant for the second experimental campaign in the HySEA project, which will focus on scenarios with initial turbulence and inhomogeneous gas clouds.

3 Experiments

The experimental campaign with homogeneous mixtures included 34 experiments: tests 01-14 with venting through the container doors, and tests 15-34 vented through either four, six or eight 1.0-m^3-openings in the roof [6]. The inner dimensions of the containers were 5.87 m × 2.35 m × 2.40 m, i.e. a total volume of about 33 m^2. A steel frame constructed from 200 mm × 75 mm U-beams (UNP) protected the internal pressure transducers and signal cables, and supported one or two obstacles: a basket with 20 high-pressure gas bottles, 50-litre each and 5 mm spacing between the bottles (B), and a pipe rack with four layers of pipes (P). Figure 1 shows the dimensions of the steel frame and the pipe rack obstacle. Eighth internal pressure sensors were positioned at the U-beams, along the side walls of the container, in the same position as the eight bolts fixing the frame to a solid foundation underneath the container, 85 mm from the side wall, and 200 mm above the floor of the container. Figure 2 shows vertical cross-sections of experimental configurations: each obstacle could be fixed in inner (1), centre (2) or outer (3) position on the frame, and the ignition source (spark) was located either at the back wall (A) or at the centre of the floor (B). It was possible to install one obstacle in the inner position (e.g. P1) and the other in the outer position (e.g. B3), denoted P1 B3 for test 14. A recirculation system was used to fill the containers with homogeneous hydrogen-air mixtures. To eliminate the effect of initial turbulence, the explosive atmosphere inside the container was isolated from the recirculation system by closing remotely operated valves prior to ignition.

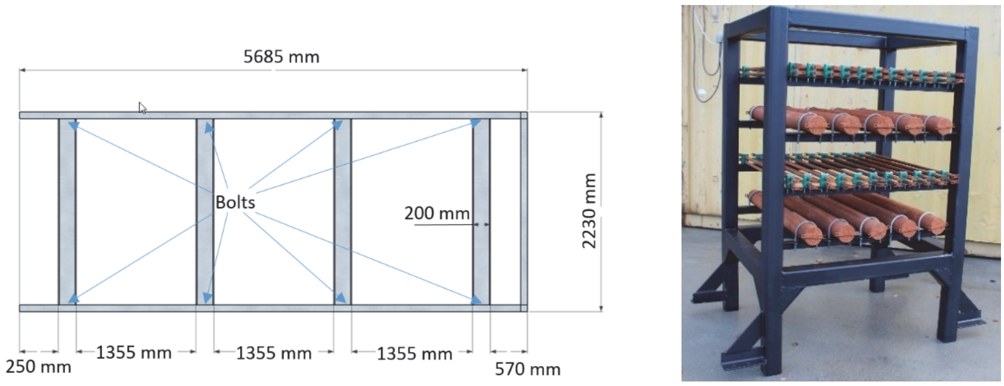

Figure 1. Steel frame and position of the eight bolts/pressure transducers (left) and pipe rack (right).

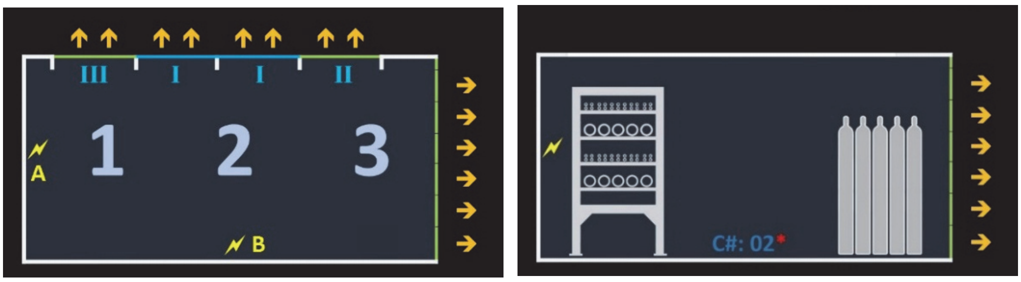

Figure 2. Illustration of obstacle/ignition positions and vent locations (left) and configuration for test 14 (right).

Table 1 summarizes experimental conditions and results for the 14 tests with venting through the container doors. The doors were fully open, positioned perpendicular to the sidewalls of the container, and the openings were covered with plastic film held in place by wooden boards and clamps. Table 2 summarizes experimental conditions and results for the tests with venting through the roof. The corrugated plate on the roof was replaced with a tailor-made steel structure with eight 1.0 m × 1.0 m openings, fixed to the steel frame inside the container. The eight openings could be sealed with plastic film, perforated along the edges, or with commercial vent panels (vent area A_v = 1 m^2 per panel, static opening pressure P_{stat} = 0.10 bar). It was possible to close up to four of the eight openings. Except from test 34, the experiments focused on mixtures with 15-24 vol.% hydrogen in air [H_2]. The first campaign consumed five containers (last test: *).

Table 1: Summary of the experiments with venting through the container doors – ignition at back wall (centre).

Configuration	Test	A_v (m^2)	[H_2] (vol.%)	Ign. pos.	$P_{red,\,max}$ (bar)
Frame only (FO), doors open (O)	01	5.64	15	A	0.040
	02	5.64	15	A	0.047
	05	5.64	15	A	0.039
Bottle basket (B1), doors open (O)	03	5.64	15	A	0.077
	04	5.64	15	A	0.064
	06	5.64	15	A	0.045
	10	5.64	18	A	0.130
	07	5.64	21	A	0.190
	08	5.64	24	A	0.390
Bottle basket (B1), doors closed (C)	09*	0.00	24	A	1.447
Pipe rack (P1), doors open (O)	11	5.64	15	A	0.050
	12	5.64	18	A	0.120
	13	5.64	21	A	0.279
Pipe rack and bottle basket (P1 B3), doors open (O)	14*	5.64	21	A	0.939

Table 2: Summary of experiments with venting through the container roof – ignition at floor (centre).

Configuration	Test	A_v (m^2)	[H_2] (vol.%)	Ign. pos.	$P_{red,\,max}$ (bar)
Frame only (FO), perforated plastic film (O)	25	4.0	21	B	0.146
	21	6.0	21	B	0.120
	16	8.0	21	B	0.190
Pipe rack (P2), perforated plastic film (O)	24	4.0	21	B	0.150
	22	6.0	21	B	0.142
	17	8.0	21	B	0.124
Pipe rack (P2), perforated plastic film (O)	34*	8.0	42	B	1.076
Pipe rack (P2), perforated plastic film (O)	29	4.0	24	B	0.414
	23	6.0	24	B	0.168
	19	8.0	24	B	0.136
Frame only (FO), commercial vent panels (P)	32	4.0	21	B	0.214
	26	6.0	21	B	0.245
	15	8.0	21	B	0.191
Pipe rack (P2), commercial vent panels (P)	33	4.0	21	B	0.261
	27	6.0	21	B	0.301
	31	6.0	21	B	0.249
	18	8.0	21	B	0.234
	30	8.0	21	B	0.214
Pipe rack (P2), commercial vent panels (P)	28*	6.0	24	B	0.45 / 0.73 ?
	20*	8.0	24	B	0.334

4 Results

Figure 3 summarizes the results from the tests with explosion venting through the doors. The highest pressures are measured in the closed end of the container, and the external pressures, i.e. side-on pressures measured with pressure transducers mounted on skimmer plates, located 5, 10 and 15 m from the vent opening (i.e. door plane), decay outside the container. In test 09, with the doors closed, the container ruptured at the back wall, and both doors were thrown a considerable distance. The back wall of the container ruptured in test 14 as well, which is the only test with both obstacles installed inside the container.

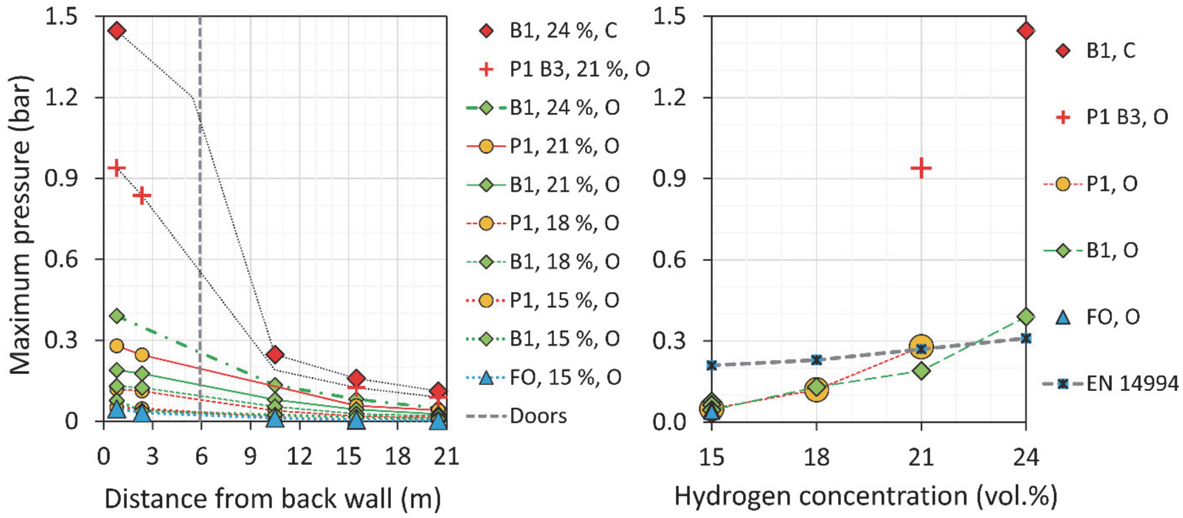

Figure 3. Maximum pressure vs. distance from back wall (left) and hydrogen concentration (right) for tests 1-14.

Figure 4 summarizes the results for the tests with venting through the roof. The containers were severely deformed in tests 20 and 28 (P2, 24 %, P). The uncertainty (?) in the maximum pressure for test 28 is due to a deviating pressure signal from one of the eight internal sensors. Tests with vent panels show consistently higher pressures compared to tests with perforated plastic film, for otherwise identical conditions. The effect of increasing the vent area is most pronounced for the more reactive mixtures. Figure 5 shows selected frames from some of the tests. The frames from test 18 show the opening of vent panels.

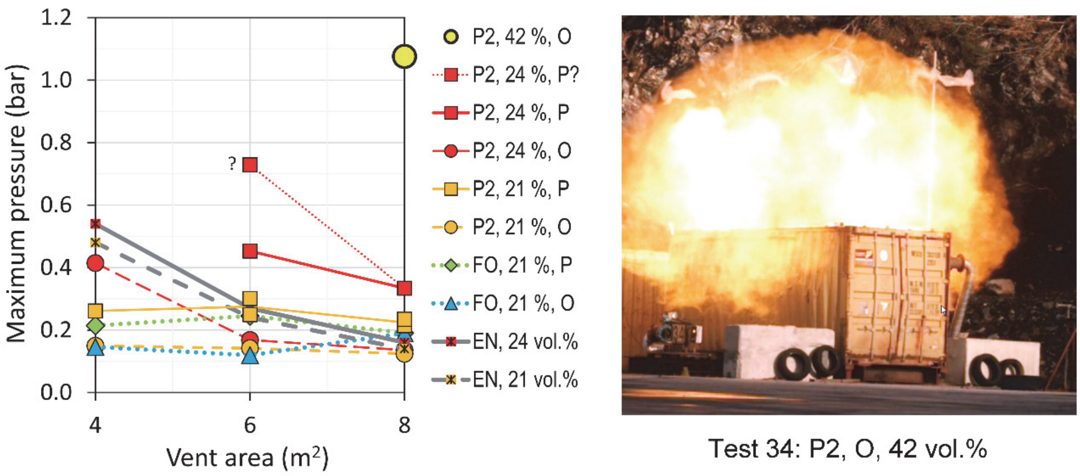

Figure 4. Maximum pressure vs. vent area for tests 15-34 (left) and vented explosion in test 34.

Figure 5. Selected frames from test 09 (top), test 14 (middle) and test 18 (bottom).

5 Discussion

The experimental campaign with homogeneous hydrogen-air mixtures ignited to deflagration in 20-foot ISO containers, conducted as part of the HySEA project, produced valuable data that can be used for validating engineering models and CFD tools. Most of the 34 experiments included measurements of the structural response of the container walls, and these results are suitable for validating FE models, including the coupling between CFD and FE tools. Noise and drift in measured pressure signals were a problem in some of the tests. Unfortunately, the range of experimental conditions that could be investigated was somewhat limited, partly due to the available budget, and partly because of the limited strength of the ISO containers.

Figures 3 and 4 include over-pressure predictions obtained with the European standard EN 14994 [2]. The empirical correlation in this standard is only valid for empty enclosures, and flammable atmospheres with gas explosion constant $K_G \leq 550$ bar m s^{-1} (i.e. mixtures with less than about 26 % hydrogen in air). These estimates involve the use of published K_G values for the relevant hydrogen concentrations [7], which implies significant uncertainty since flame wrinkling and other instabilities cause the experimentally determined K_G values to vary significantly with the volume and shape of the test vessel.

Furthermore, since the EN standard assumes a static opening pressure P_{stat} of 0.10 bar, the correlation over-predicts P_{red} for tests with low reactivity and vent openings covered by plastic film (O). The effect of internal congestion on P_{red} increases for the more reactive fuel-air mixtures, and the standard significantly under-predicts the explosion pressure for tests with internal congestion and 24 vol.% hydrogen in air.

Test 09, with the container doors closed, serves as a reminder of the hazard posed by projectiles: one door bounced off the gravel on the side of the container, hit the hillside some 10 m above ground, and landed about 30 m from the container. The container ruptured at an internal overpressure of about 1.1-1.3 bar.

Test 14, with both obstacles installed inside the container (P1 B3), demonstrates the strong effect internal congestion can have on vented explosions. The reason for the high over-pressures observed in this test is presumably a combination of flame acceleration through the pipe rack (P1) and the blocking effect of the bottle basket located near the vent opening (B3).

The significant increase in P_{red} from tests 23 and 19 (i.e. P2, 24 vol.%, O) to tests 28 and 20 (i.e. P2, 24 vol.%, P), for A_v = 6.0 and 8.0 m^2 in Figure 4, suggests that vent panels with lower opening pressure and/or lower mass can provide more effective protection of relatively weak structures, such as shipping containers. However, the results obtained for test 34, with 42 vol.% hydrogen, shows that there are inherent limitations to the level of protection that can be achieved for explosions involving more reactive mixtures. Initial turbulence, produced by forced ventilation or the leak itself, may also increase the rate of combustion and hence the maximum pressure.

6 Conclusions and further work

The first part of the experimental study of vented hydrogen deflagrations in 20-foot ISO containers in the HySEA project produced valuable validation data for modellers [6]. The results demonstrate the strong effect of congestion on vented deflagrations, especially for the more reactive mixtures. The validation of CFD and FE models in the HySEA will entail direct comparison between experimental results and model predictions. It is foreseen that this process will result in improved understanding of the physical and chemical phenomena involved in vented hydrogen deflagrations. The next experimental campaign in 20-foot containers will focus on deflagrations in inhomogeneous mixtures, resulting from more realistic releases, with or without forced ventilation in the enclosure. The experimental results from the HySEA project are particularly well suited for testing and validating engineering models for vented hydrogen deflagrations, and hence for improving the empirical correlations for design of venting devices in international standards such as EN 14994 [2] and NFPA 68 [3].

Acknowledgements

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