CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977115

Vented Hydrogen Deflagrations in Weak Enclosures: Experimental Results and Implications for Industrial Practice

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It is common practice in industry to install equipment for hydrogen energy applications in containers and smaller enclosures. Fires and explosions represent a significant hazard for such installations (Skjold et al., 2018), and specific measures are generally required for reducing the risk to a tolerable level (Skjold et al., 2017). Explosion venting is a frequently used measure for mitigating the consequences of hydrogen deflagrations in confined systems. Whereas most enclosures used for hydrogen applications in industry are inherently congested, most of the experiments that have been used for validating the empirical or semi-empirical engineering models in international standards, such as EN 14994 (2007) and NFPA 68 (2018), were performed with empty vessels. This paper reviews selected results from the experimental investigation of vented hydrogen deflagrations performed in 20-foot ISO containers as part of the EU-funded HySEA project (Skjold 2018ab; Skjold et al., 2019a). The parameters investigated in the experiments include hydrogen concentration, vent area, type of venting device, homogeneous and inhomogeneous mixtures, initial turbulence and level of congestion inside the enclosures. The measurements included maximum reduced explosion pressure, external blast waves and the structural response of the container walls. The results demonstrate the strong effect of congestion and mixture stratification on the maximum reduced explosion pressure, neither of which is accounted for in the current version of the European standard for gas explosion venting protective systems (EN 14994, 2007). The discussion elaborates on the implications of the results for industrial applications.

1. Introduction

Various researchers have studied vented hydrogen deflagrations in the past, but often in explosion vessels of modest size, with improvised explosion venting devices, and primarily in empty enclosures. Bauwens et al. (2011, 2012) and Bauwens and Dorofeev (2014) reported results for explosions in a 64-m^3 chamber at FM Global, including the effect of obstacles and initial turbulence. As part of the HyIndoor project, the UK Health and Safety Laboratory (HSL) performed tests in a 31-m^3 low-strength (100 mbar) enclosure (Hooker et al., 2017). Sommersel et al. (2017) performed tests with inhomogeneous mixtures, initial turbulence and varying degrees of congestion in a 20-foot ISO container. In general, the overpressures measured in vented deflagration experiments tend to increase with increasing reactivity of the mixture, decrease with increasing vent area, increase with increasing opening pressure and specific weight of the venting device, and increase with increasing distance from the point of ignition to the vent opening. For the same total mass of hydrogen inside the enclosure, stratified mixtures can produce significantly higher explosion pressures compared to homogeneous lean mixtures. The presence of obstacles tends to dampen acoustic instabilities, but flame propagation past obstacles results in increased flame surface area and enhanced turbulence in the wakes – the net result will in most situations be higher overpressures. For lean hydrogen-air mixtures, both flame speeds and deflagration overpressures can be significantly higher than for typical hydrocarbon-air mixtures with the same laminar burning velocity. Two blind-prediction benchmark studies conducted as part of the HySEA project demonstrated the limited predictive capabilities of engineering models for estimating the maximum reduced explosion pressure in vented hydrogen deflagrations. These studies included

Paper Received: 19 December 2018; Revised: 22 April 2019; Accepted: 12 July 2019

Please cite this article as: Skjold T., 2019, Vented hydrogen deflagrations in weak enclosures: experimental results and implications for industrial practice, Chemical Engineering Transactions, 77, 685-690 DOI:10.3303/CET1977115

computational fluid dynamics (CFD) tools and simpler models based on empirical or semi-empirical correlations (Skjold et al., 2019bc).

2. Experiments

The scenarios investigated in the HySEA project included 42 tests with initially homogeneous and quiescent mixtures (14 tests vented through the doors, one test with closed container, and 27 tests vented through openings on the roof), and 24 tests with inhomogeneous mixtures (17 tests with stratified mixtures and 7 tests with initial turbulence generated by either a fan or a transient jet). The total number of tests was 72, which included five unignited tests and one failed test. A steel frame on the floor supported the obstacles and protected the signal cables for the pressure sensors located inside the container (mounted on the frame). Tests without obstacles, i.e. nearly empty container, were denoted frame only (FO). The bottle basket obstacle (B) and the pipe rack obstacle (P) could be placed in inner (1), middle (2) or outer (3) position. Figure 1 shows a 20-foot ISO container before testing (left), the bottle basket and pipe rack obstacles (centre), and the interior of a container with vent panels in the ceiling and the pipe rack obstacle in the centre position (denoted P2). Skjold (2018ab) and Skjold et al. (2019abc) describe the experimental setup and procedures in detail.

Figure 1: Container (left), bottle basket and pipe rack obstacles, and interior of container with pipe rack (right).

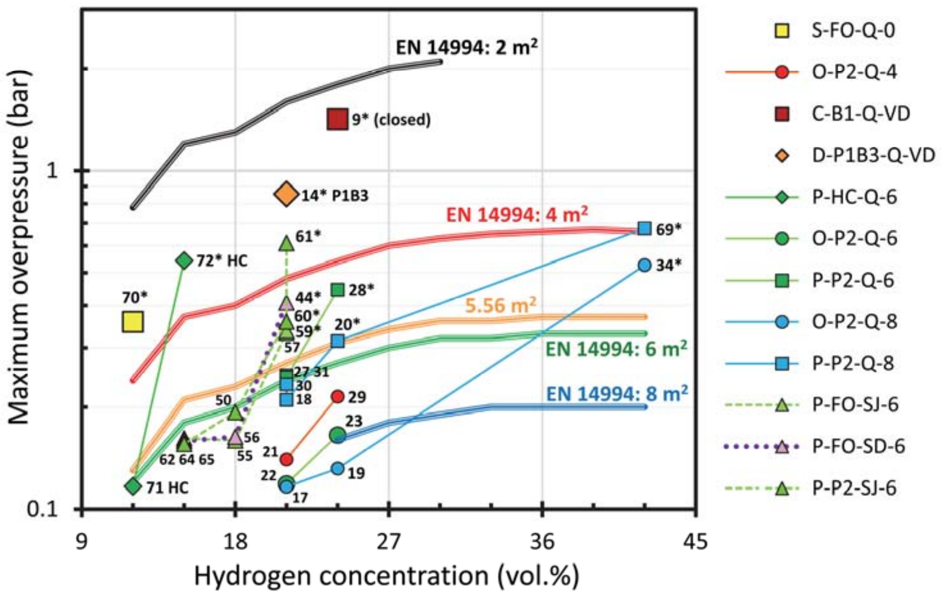

Figure 2: Maximum explosion pressures for the 30 tests from Table 1 and predictions according to EN 14994.

3. Results

Table 1 summarises the test configurations and selected results for 30 of the 66 vented deflagration tests, including the tests that resulted in the highest overpressures and the most severe structural damage. Twelve used containers from the same manufacturing series were damaged beyond repair, and the twelve test numbers marked with an asterisk indicate the last tests with one of the containers (i.e. tests resulting in severe structural damage). The venting device ('Vent') was either perforated polyethylene film (O) or commercial vent panels with static opening pressure 0.1 bar (P). In test no. 9, the container doors were initially closed (C) but opened during the test (Figure 3a). The purpose of test no. 70 was to investigate the structural response resulting from a quasi-static pressure load. The doors remained closed (S) in this test, but some leakage occurred. Three ignition positions ('Ign.') were used: back wall centre (bc), back wall upper (bu), and floor centre (fc). The obstacle configuration ('Obst.') used in most tests involved frame only (FO) or frame with only one of the two obstacles shown in Figure 1 (B1, P1 or P2). However, test no. 14 included two obstacles (P1B3), with the bottle basket partly blocking the vent opening. Furthermore, tests 71 and 72 explored the effect of significantly higher levels of congestion (HC) for lean hydrogen-air mixtures (12 and 15 vol.%). The initial conditions for the flammable mixture ('Flow') were either initially quiescent and homogeneous mixture (Q), or stratified mixture generated by a vertical jet (SJ) or a vertical diffusive release.

Table 1: Results from 30 of the 66 experiments in 20-foot ISO containers (Skjold et al., 2019a).

Test	C_{H2} (vol.%)	A_v (m^2)	Vent	Ign.	Obst.	Flow	P_{max} (bar)	P_m (bar)	D_m (m)	D_p (m)	$(dP/dt)_m$ (bar/s)	I_m (bar ms)
70*	12	~0	S	bu	FO	Q	0.36	0.34	0.19	0.065	1.0	397
24	21	4.0	O	fc	P2	Q	0.14	0.12	0.07	0.003	4.4	5.1
29	24	4.0	O	fc	P2	Q	0.22	0.22	0.17	0.069	12	15
9*	24	5.56	C	bc	B1	Q	1.42	1.30	—	—	46	48
14*	21	5.56	D	bc	P1B3	Q	0.85	0.79	0.29	0.103	46	19
71	12	6.0	P	fc	HC	Q	0.12	0.11	0.05	0.002	1.3	11
72*	15	6.0	P	fc	HC	Q	0.54	0.46	0.36	0.278	25	14
22	21	6.0	O	fc	P2	Q	0.12	0.11	0.07	0.012	5.2	3.9
23	24	6.0	O	fc	P2	Q	0.17	0.15	0.09	0.026	7.8	4.4
27	21	6.0	P	fc	P2	Q	0.25	0.23	0.16	0.042	8.1	9.0
31	21	6.0	P	fc	P2	Q	0.25	0.22	0.15	0.016	6.7	8.2
28*	24	6.0	P	fc	P2	Q	0.45	0.31	0.17	0.081	12	8.6
17	21	8.0	O	fc	P2	Q	0.12	0.11	0.06	0.006	4.8	3.8
19	24	8.0	O	fc	P2	Q	0.13	0.12	0.06	0.014	6.1	4.1
34*	42	8.0	O	fc	P2	Q	0.53	0.42	—	—	15	32
18	21	8.0	P	fc	P2	Q	0.23	0.21	0.16	0.040	8.5	7.6
30	21	8.0	P	fc	P2	Q	0.21	0.18	—	—	6.2	7.1
20*	24	8.0	P	fc	P2	Q	0.31	0.29	0.17	0.083	11	8.9
69*	42	8.0	P	fc	P2	Q	0.68	0.58	0.59	0.476	32	13
65	15	6.0	P	bu	FO	SJ	0.16	0.16	0.10	0.000	3.9	6.7
55	18	6.0	P	bu	FO	SJ	0.16	0.15	0.09	0.009	3.5	6.6
57*	21	6.0	P	bu	FO	SJ	0.33	0.26	0.18	0.042	11	7.9
59	21	6.0	P	bu	FO	SJ	0.34	0.26	0.17	0.030	9.6	8.0
64	15	6.0	P	bu	FO	SD	0.16	0.15	0.09	0.000	3.7	6.8
56	18	6.0	P	bu	FO	SD	0.16	0.15	0.09	0.008	3.5	6.8
44*	21	6.0	P	bu	FO	SD	0.41	0.32	0.16	0.071	14	8.6
62	15	6.0	P	bu	P2	SJ	0.16	0.14	0.07	0.009	3.0	6.7
50	18	6.0	P	bu	P2	SJ	0.19	0.18	0.12	0.006	5.5	7.0
60*	21	6.0	P	bu	P2	SJ	0.36	0.28	0.19	0.064	10	10
61*	21	6.0	P	bu	P2	SJ	0.61	0.43	0.38	0.263	17	12

Figure 2 compares the maximum explosion pressures for the 30 tests summarised in Table 1 with predictions according to the European standard for explosion venting protective systems (EN 14994, 2007). The empirical correlations in the standard are only applicable for empty enclosures and flammable atmospheres with gas explosion constants $K_G \leq 550$ bar m s^{-1}, corresponding to the reactivity of hydrogen-air mixtures with hydrogen concentrations in the range 22-28 vol.%. The model predictions in Figure 2 were obtained using values for the maximum rate of pressure rise and the maximum explosion pressure measured in a 6-litre vessel (Holtappels, 2006) as input to the software package WinVent 4.0. This approach implies significant uncertainty since flame wrinkling and other instabilities cause experimentally determined K_G values to vary significantly with the volume and shape of the test vessel. Furthermore, since the correlations in EN 14994 assume a static opening pressure P_{stat} of 0.10 bar, the model over-predicts the reduced explosion pressure for tests with low reactivity mixtures and vent openings covered by polyethylene film. Figure 3 shows selected frames from six of the 66 vented deflagration tests: test 9 with venting through the container doors (a), test 14 with venting through a polyethylene sheet covering the opening of the container doors (b), test 28 with six 1-m^3 commercial vent panels on the roof (c), test 34 with 42 vol.% hydrogen in air and venting through eight 1-m^3 vent openings covered by perforated polyethylene film (d), and tests 59 (e) and 72 (f) with six 1-m^3 commercial vent panels on the roof.

Figure 3: Selected frames from six vented deflagration tests.

This paper focuses on the results from the measurements of internal pressures and wall deflection: maximum reduced explosion pressure P_{max}, average maximum reduced explosion pressure P_m, average maximum rate of pressure rise $(dP/dt)_m$, average pressure impulse I_m, average maximum deflection D_m and average permanent deformation D_p. The final report describes the data analysis and includes additional data, such as the pressures measured by the external blast gauges P09-P11, the time t_{stat} when the venting devices start to open, and the time it took for the commercial vent panels to open 45, 90 and 180 degrees (Skjold, 2018ab).

4. Discussion

The main application of the results from the vented hydrogen deflagration tests in the HySEA project is the validation of empirical or semi-empirical engineering models (Lakshmipathy et al., 2019), as well as computational fluid dynamics (CFD) tools for hydrogen safety applications. The experiments included measurements of the structural response of the container walls to internal pressure loads, and this information can be used for validating finite element (FE) models and the coupling between CFD and FE tools (Atanga et al., 2019). However, the range of experimental conditions that could be investigated in the HySEA project was limited, partly due to the available budget, and partly because of the limited strength of 20-foot ISO containers. The fact that the same container was used in several tests influenced the repeatability of the experiments. In the context of vented deflagrations, shipping containers are relatively weak structures. The structural response measurements revealed significant deflection of the container walls, even for relatively modest pressure loads. Hence, the volume of the enclosures varied significantly during some of the tests, especially for some of the more violent explosions, and this effect should be considered when using the results for model validation.

The vent panel opened simultaneously in most of the tests with commercial panels. The main structure of the container remained intact in all tests, except from test 9 where the hinges broke when the doors opened. One door bounced off the gravel on the side of the container, hit the hillside some 10 m above the ground, and landed about 30 m from the container. This demonstrates the hazard posed by projectiles and highlights the importance of securing attached structural elements such as doors, louvre panels and ventilators. The container doors do not represent proper explosion venting devices according to the European standard (EN 14797, 2006). The containers walls ruptured in some of the tests that produced high overpressures (e.g. test 9 in Figure 3a). The smoothing frequency used for processing the experimental pressure-time curves influenced the results (Skjold, 2018ab; Skjold et al., 2019a), but primarily for the maximum rate of pressure rise. The finite rise time of the pressure loads and the high level of plasticity of the corrugated plates in the walls and roof complicate the analysis of the structural response (Baker et al., 1983). Furthermore, it is not straightforward to calculate unambiguous values for pressure impulse for tests with multiple pressure peaks.

Since most of the tests involved lean mixtures, i.e. less than 30 vol.% hydrogen, the maximum reduced explosion pressures increase consistently with increasing fuel concentration for all obstacle and vent configurations. Tests 34 (O) and 69 (P) with rich mixtures (42 vol.% hydrogen) were included to explore close to worst-case conditions for a modest degree of congestion (P2). Figure 2 shows that the maximum pressures increase more rapidly for tests with internal congestion, compared to the predictions by EN 14994 (2007). The results for tests 71 and 72 demonstrate the strong effect higher levels of congestion (HC) can have on the maximum reduced explosion pressure, even for a modest increase in concentration (from 12 to 15 vol.%) for lean hydrogen-air mixtures. None of the 66 tests vented deflagration tests in 20-foot ISO containers resulted in detonations. However, tests with more reactive mixtures in the high-congestion (HC) geometry would most likely have resulted in deflagration-to-detonation-transition (DDT). Safe design of hydrogen installations should also consider the possibility of DDT in connection with accident scenarios that involve high-pressure releases, local confinement (e.g. instrumentation cabinets) and flame propagation in ducts (e.g. ventilation channels).

Figure 3d shows the external flame in test 34 with 42 vol.% hydrogen and 0.2 mm polyethylene film used as vent cover. The pressure-time histories from this test revealed a distinct secondary peak with significant amplitude and duration (Skjold, 2018a). This observation was consistent for all the eight internal pressure sensors. It is possible that the external explosion blocked the outflow from the container, and that rapid afterburning of remaining fuel inside the container produced the secondary peak. Since the data acquisition system shut down during the test, it is not clear whether test 69, with 42 vol.% hydrogen and commercial vent panels, produced a similar peak. Nevertheless, the results from tests 34 and 69 demonstrate that explosion protection by venting can be effective for 20-foot ISO containers under near worst-case conditions, as long as severe structural damage is acceptable, and provided DDT does not occur.

Loss of containment of gaseous hydrogen in confined spaces will normally result in buoyant releases and stratified fuel-air clouds. The significantly higher overpressures obtained for stratified mixtures, compared to lean homogeneous mixtures with the same total mass of fuel, imply that models for vented hydrogen deflagrations should account for the effect of inhomogeneous fuel-air clouds. The second blind-prediction benchmark exercise in the HySEA project explored the predictive capabilities of consequence models with respect to simulating vented deflagrations resulting from stratified hydrogen-air mixtures ignited to deflagration in 20-foot ISO containers (Skjold et al., 2019c). Although some of the results were encouraging, especially for the modelling of release and dispersion scenarios, there is significant room for improving the predictive capabilities of the model systems and the modellers.

5. Conclusions

The experimental study of vented hydrogen deflagrations in 20-foot ISO containers in the HySEA project produced valuable validation data for modellers. The results demonstrate the strong effect of congestion on vented deflagrations and a rapid increase in explosion violence for increasingly reactive mixtures and higher levels of congestion. The results also highlight the importance of considering projectiles, including the container doors, in risk assessments and design. Future verification and validation of CFD and FE models will entail direct comparison between experimental results and model predictions, and it is foreseen that this process will result in improved understanding of the physical and chemical phenomena involved in vented hydrogen deflagrations. 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 explosion venting protective systems (EN 14994, 2007) and explosion venting devices (EN 147979) in international standards.

Acknowledgements

The author gratefully acknowledges the members of the HySEA consortium: Gexcon, University of Warwick, University of Pisa, Fike Europe, Impetus Afea and Hefei University of Technology. The HySEA project received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No. 671461.

This Joint Undertaking received support from the European Union's Horizon 2020 research and innovation programme and the United Kingdom, Italy, Belgium and Norway.

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