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Experimental studies on vented deflagrations in a low strength enclosure☆

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ABSTRACT

This paper describes an experimental programme on vented hydrogen deflagrations, which formed part of the Hyindoor project, carried out for the EU Fuel Cells and Hydrogen Joint Undertaking. The purpose of this study was to investigate the validity of analytical models used to calculate overpressures following a low concentration hydrogen deflagration. Other aspects of safety were also investigated, such as lateral flame length resulting from explosion venting. The experimental programme included the investigation of vented hydrogen deflagrations from a 31 m^3 enclosure with a maximum internal overpressure target of 10 kPa (100 mbar). The explosion relief was provided by lightly covered openings in the roof or sidewalls. Uniform and stratified initial hydrogen distributions were included in the test matrix and the location of the ignition source was also varied. The maximum hydrogen concentration used within the enclosure was 14% v/v. The hydrogen concentration profile within the enclosure was measured, as were the internal and external pressures. Infrared video images were obtained of the gases vented during the deflagrations. Findings show that the analytical models were generally conservative for overpressure predictions. Flame lengths were found to be far less than suggested by some guidance. Along with the findings, the methodology, test conditions and corresponding results are presented.

Introduction

Hydrogen energy applications may require that systems be used inside rooms or enclosures (e.g. for security reasons). The accidental release of hydrogen within a room or enclosure can potentially lead to the formation of a flammable mixture and an explosion. In this context it is necessary to understand the explosion relief required to limit the overpressures arising from deflagrations of hydrogen accumulations to an acceptable level, typically of the order of 10 kPa (100 mbar) for iso-container type structures. There were knowledge gaps in predicting deflagration over-pressures for such installations and so models were investigated and experiments were carried out for the European Union (EU) Fuel Cells and Hydrogen Joint Undertaking (FCH JU) project “HyIndoor”

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Nomenclature

K_G	gas explosion constant, bar m s^{-1}
S_u	laminar burning velocity of the flammable mixture, m s^{-1}
L_F	lateral flame length from the explosion vent, m
V	volume of the enclosure, m^3

(http://www.hyindoor.eu). This paper describes experiments that were carried out by the United Kingdom's Health and Safety Laboratory (HSL) and comparison of the results obtained with analytical models. The hydrogen mixtures used were lean, up to 14% v/v, in order to restrict the maximum explosion over-pressure when using practical explosion relief vent areas. Clearly, this does not include more catastrophic losses of containment where higher concentrations and more severe consequences, such as detonations, may occur. In order to adopt a limited approach to explosion pressure relief as described here, other mitigating measures would need to be employed.

Pre-test modelling

One issue of practical concern to those involved in specifying explosion relief for industrial structures has been the limited availability of reliable predictive methods for hydrogen. To illustrate this, pre-test calculations were carried out by HSL using a number of methods available in the literature at the start of the Hyindoor project, using the design pressure of the HSL enclosure, 20 kPa, as a maximum. The vent opening pressure, P_{stat}, was set to zero as the actual vent opening pressure was not determined at this time.

HSL carried out calculations using EN 14994:2007 "Gas explosion venting protective systems" [1] and the models described by Molkov and co-workers [2,3]. Note that at the start of the project the equations used for predicting overpressure in the NFPA68 Standard on Explosion Protection by Deflagration Venting (2007) [4] were the same as those in EN 14994:2007.

EN 14994:2007

EN 14994:2007 can be used to calculate the minimum explosion venting area, but can also be used to estimate gas explosion pressures within a vented enclosure. The approach uses a gas explosion constant, K_G, which has units of bar m s^{-1}. Although EN 14994:2007 has a limit of 500 bar m s^{-1} which would invalidate its use for hydrogen mixtures approaching stoichiometric, its use for lean hydrogen mixtures may appear to be reasonable, since the K_G value for lean mixtures will be less than 500 bar m s^{-1}. K_G was estimated using the approach described in NFPA68 (2007) [4],

$$K_G = K_{G,ref} \times S_u / S_{u,ref}, \quad (1)$$

where S_u is the laminar burning velocity of the flammable mixture. The calculations were based on reference values of $K_{G,ref}$ = 550 bar m/s and $S_{u,ref}$ = 3 m/s. The laminar burning velocity, S_u, for each mixture was taken from Koroll et al. [5] and Bragin [6]. The values from Bragin (2012) are much slower and therefore less conservative than the values from Koroll et al. (1993). Note that the method given in EN 14994:2007 is applicable to cases where P_{stat} is at least 100 mbar (10 kPa) and so its use in this situation is outside the normal range.

Molkov models (pre-2011)

HSL used the Molkov models described by Molkov [2,3]. In the model described by Molkov et al. (1999), the explosion pressure is calculated from the turbulent Bradley number; the model described by Molkov (2001) is essentially a conservative version of the model described by Molkov et al. (1999). The laminar burning velocities used were as described in Section EN 14994:2007.

Results of pre-test calculations

The engineering models described in the previous sections were used to estimate explosion pressures in the HSL test facility for a range of initial hydrogen concentrations (up to 15% v/v) and vent areas (up to 6.4 m^2). The hydrogen concentration refers to the molar fraction and was assumed to be uniform throughout the enclosure. The HSL enclosure has vents in the roof and sidewalls. The roof vents are relatively large (0.8 m^2) and their sole purpose is to provide explosion relief (i.e. under normal operation they are covered by a suitable explosion relief panel). Conversely, the sidewall vents (hereafter referred to as passive vents) are relatively small (0.23 m^2) and their primary function is to provide passive ventilation of unignited releases.

Results are presented in Table 1 (note that calculations were not always carried out for cases where the estimated pressure rise was clearly going to exceed 20 kPa, marked as "–" in the table). As shown in Table 1, there was considerable variation in the results. For example, the overpressure for a hydrogen concentration of 15% v/v and vent area of 6.4 m^2 varied between 3 kPa (calculated using Molkov et al., 1999 with laminar burning velocity from Bragin, 2012) and 7.3 kPa (calculated using Molkov, 2001 with laminar burning velocity from Koroll et al., 1993). Overall, the model described by Molkov (2001) was more conservative than the EN 14994:2007 calculations, which were more conservative than the model described by Molkov et al. (1999).

Note that a further model applicable to weak enclosures was published by Molkov and Bragin [7] during the Hyindoor project and the fit of the HSL experimental data to that model is discussed in Section Post-test comparison with improved correlation for overpressure calculation.

Experimental details

Test matrix

The experimental work at HSL involved three distinct test series.

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