GAS TURBINE ENCLOSURES: DETERMINING VENTILATION SAFETY CRITERIA USING HYDROGEN EXPLOSION MODELLING

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ABSTRACT

Dilution ventilation is the current basis of safety following a flammable gas leak within a gas turbine enclosure, and compliance requirements are defined for methane fuels in ISO 21789. These requirements currently define a safety criteria of a maximum flammable gas cloud size within an enclosure. The requirements are based on methane explosion tests conducted during a HSE Joint Industry Project, which identified typical pressures associated with a range of gas cloud sizes. The industry standard approach is to assess the ventilation performance of specific enclosure designs against these requirements using CFD modelling. Gas turbine manufacturers are increasingly considering introducing hydrogen/methane fuel mixtures and looking towards operating with hydrogen alone. It is therefore important to review the applicability of current safety standards for these new fuels, as the pressure resulting from a hydrogen explosion is expected to be significantly higher than that from a methane explosion. In this paper, we replicate the previous methane explosion tests for hydrogen and hydrogen/methane fuel mixtures, using the explosion modelling tool FLACS CFD. The results are used to propose updated limiting safety criteria for hydrogen fuels to support ventilation CFD analysis for specific enclosure designs. It is found that significantly smaller gas cloud sizes are likely to be acceptable for gas turbines fueled by hydrogen, however, significantly more hydrogen than methane is required per unit volume to generate a stoichiometric cloud (as hydrogen has a lower stoichiometric air fuel ratio than methane). This effect results in the total quantity of gas in the enclosure (and as such, detectability of the gas) being broadly similar when operating gas turbines on hydrogen when compared to methane.

1.0 INTRODUCTION

1.1 EXISTING ENCLOSURE SAFETY REQUIREMENTS

In most cases gas turbine enclosures cannot directly comply with the ATEX Directives 94/9/EC and 2014/34/EU because of the proximity of hot gas turbine surfaces to fuel systems and piping. ATEX compliance is therefore achieved on the basis of dilution ventilation, whereby the ventilation system is demonstrated to prevent the buildup of a significant flammable cloud following a breach in the fuel system within the enclosure. In practice, this demonstration is made by using Computational Fluid Dynamics (CFD) assessment to confirm compliance with the specific safety criteria defined in ISO 21789 [1]. These safety criteria state that ventilation within the enclosure should be sufficient that the equivalent stoichiometric volume of the flammable gas cloud resulting from a leak does not exceed 0.1% of the enclosure volume, so that in the event of ignition, the resulting pressure increase will not exceed 10 mbar. This 10 mbar pressure limit is used to avoid significant damage to an enclosure or risk of injury to persons outside of the enclosure [2]. Gas detectors are then installed to ensure that any leaks resulting in gas clouds larger than this criteria are detected and the fuel supply isolated. The basis for the 0.1% enclosure volume criteria is a series of tests undertaken during a UK Health and Safety Executive Joint Industry Project (HSE JIP) to determine likely pressure increases following ignition of methane clouds inside a representative enclosure [3].

1.2 IMPLICATIONS FOR OPERATION WITH HYDROGEN

There is currently significant interest in using hydrogen as a fuel, and one proposed use is for power generation using gas turbines. One of the key challenges associated with converting gas turbines to run on hydrogen is the enclosure safety aspects, since previous work has indicated that hydrogen typically generates a greater pressure increase than methane when a gas cloud of a similar size is ignited [4] [5]. This higher overpressure challenges the basis for the existing equivalent stoichiometric volume criteria (of 0.1% of enclosure volume) defined in ISO 21789.

1.3 OBJECTIVES

This paper presents an approach used to develop a new criteria for the maximum stoichiometric gas cloud size when operating enclosed and ventilated gas turbines with hydrogen or hydrogen/methane blends. The assessment was carried out using the explosion simulation tool FLACS CFD (FLame ACcelleration Simulator [6]). This paper:

- Develops confidence in the use of FLACS CFD through comparison with experimental data generated by the HSE JIP;
- Identifies the resulting overpressures if the current ISO 21789 safety criteria of 0.1% of enclosure volume is applied when operating with hydrogen;
- Defines a new flammable gas cloud size limit for hydrogen, based on the 10 mbar overpressure criteria stated in ISO 21789 [1]. It is noted that pressure impulse may give a more representative indication of the load on the enclosure, however this paper seeks to remain consistent with the approach used in ISO 21789;
- Defines new flammable gas cloud size limits for hydrogen/methane blends, based on the 10 mbar overpressure criteria stated in ISO 21789 [1].

2.0 METHODOLOGY

2.1 FLACS CFD SOFTWARE

FLACS CFD is a CFD tool developed by Gexcon, used for dispersion and explosion modelling for the purposes of industrial safety. It is a widely used tool in high hazard industries, such as oil and gas, to help understand the implications of leakage and ignition of flammable gases.

Typically, FLACS CFD is used to model explosions of larger gas clouds than those considered here. As such, this paper contains a comparison between FLACS CFD results and experimental results at these low gas cloud sizes to help build confidence in the suitability of the tool and approach.

2.2 GEOMETRY

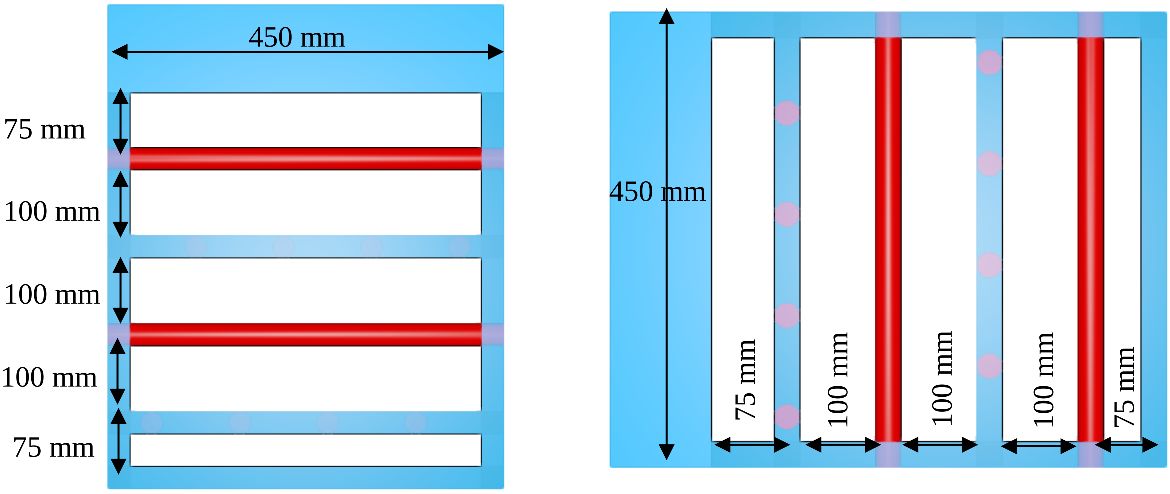
The geometry used for the FLACS CFD analysis replicates the geometry used in the HSE JIP experimental program. The geometry consists of a large enclosed cuboid volume (2.5m x 2.5m x 14.9m), with a small (0.45m x 0.45m x 0.45m) centrally located congested volume, which is filled with a quiescent flammable gas cloud and ignited on one side.

Throughout the FLACS CFD analysis, a quiescent starting condition is considered. This is consistent with the approach applied to define the original 0.1% enclosure volume criteria in the HSE JIP.

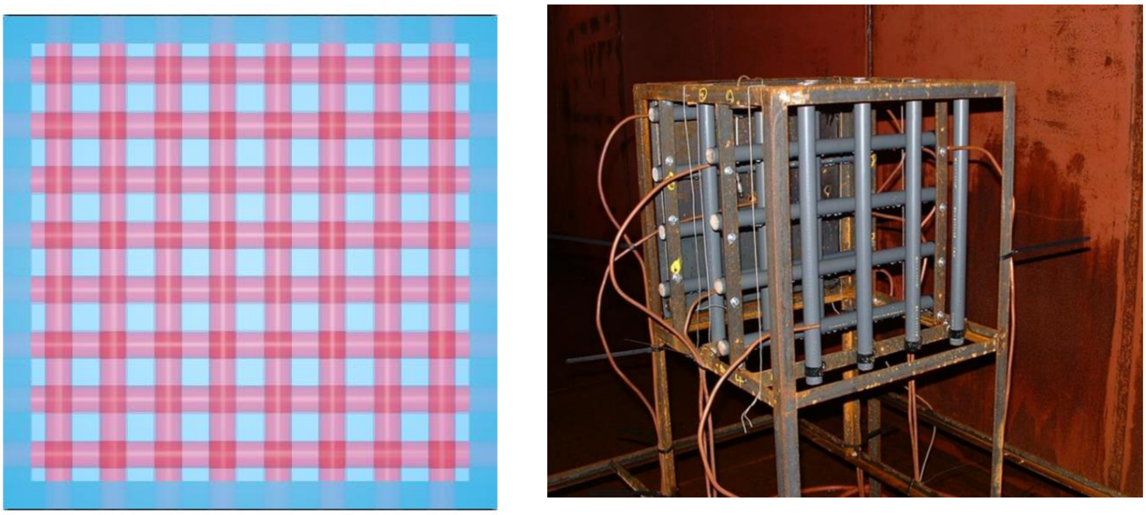
The congestion used is representative of the typical congestion seen within a gas turbine enclosure [3]. Two different congestions are considered (A and B), representing slightly different levels of congestion. Congestion A is represented in Figure 3-1. Congestion B is a similar configuration, with a slightly greater spacing between obstacles. The area and volume blockages for each congestion are reported in Table 3-1.

Table 3-1. Congestion Blockage Ratios

Congestion	**Area Blockage**			**Volume Blockage**
	X	**Y**	**Z**	
A	69.1%	13.1%	13.1%	3.9%
B	44.4%	7.0%	11.8%	2.2%



a)   FLACS CFD Geometry, Top View   b)   FLACS CFD Geometry, Side View



c)   FLACS CFD Geometry, End View   d) HSE JIP Geometry [3]

Figure 3-1. Congestion A Geometry.

Pressure is monitored at four points in the enclosure, consistent with the pressure transducer locations PT2-PT5 used in the HSE JIP analysis (PT1 is not reported, as the HSE JIP results for this transducer were not considered reliable [3]). The pressure transducer/monitor point locations are summarized in Figure 3-2 and Table 3-2.   In the HSE JIP, Kistler Model 4043A1 piezo-resistive transducers were utilised. In the FLACS analysis, monitor points, which report the transient pressure at a specified cell are used.

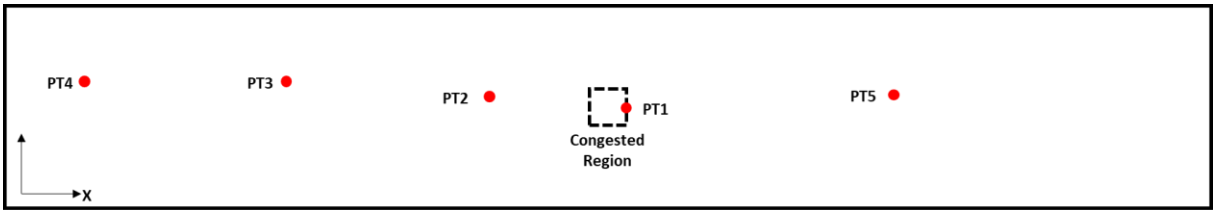


Figure 3-2. Enclosure Layout (Side View)

Table 3-2. Pressure Transducer Locations (X, Y coordinates with origin at bottom LHS of enclosure)

Pressure Transducer	Location	X [m]	Y [m]
PT1	Centre of solid wall of congested region	-	-
PT2	Enclosure wall	5.975	1.355
PT3		3.465	1.54
PT4		0.975	1.54
PT5		10.97	1.375

2.3 GRID

FLACS CFD uses a Distributed Porosity Model (DPM), and as such requires a regular Cartesian grid, with no stretching (i.e. aspect ratio of 1 throughout). To ensure good resolution of the flame front, 13 cells have been defined across each dimension (x, y and z) of the gas cloud.

When using cells below ~20 mm, the sub-grid models in FLACS CFD may artificially generate turbulence and over-predict the overpressures [6]. The minimum cell size used was 23mm to minimise potential over-prediction of turbulence that can occur with cell sizes smaller than ~20mm.

2.4 CASE SELECTION

The sets of cases assessed using FLACS CFD are:

1. **Methane Baseline**: This first set of cases is consistent with the tests performed as part of the HSE JIP, and used to build confidence in the numerical methods. These cases consider the ignition of a stoichiometric methane gas cloud equal to 0.098% of the enclosure volume, and assess the three different congestion configurations (Congestion A, Congestion B and no congestion).
2. **Hydrogen Baseline**: These cases have the same congestion configurations and cloud size as the methane baseline cases, but consider a stoichiometric hydrogen, rather than methane, gas cloud. These cases therefore predict the expected overpressures resulting from the methane gas cloud size requirement being used for hydrogen, and are also used to confirm the worst case congestion configuration.
3. **Equivalence Ratio Sensitivities:** The equivalence ratio is the ratio of air-fuel ratio to the stoichiometric air fuel ratio, where values in excess of 1 represent a rich gas cloud and values less than 1 represent a lean gas cloud (and an ER of 1 represents a stoichiometric gas cloud). A set of cases using a range of Equivalence Ratios (ER) are used to assess if different air/hydrogen mixes could lead to significantly larger overpressures.
4. **Cloud Size Sensitivities:** Cases with hydrogen cloud sizes down to the minimum cloud size compatible with the FLACS CFD grid requirements are run to identify the maximum cloud size that satisfies the 10 mbar overpressure criteria.

5. **Mixture Sensitivities:** The maximum cloud size that meets the 10 mbar overpressure criteria is identified for a range of blended hydrogen/methane compositions.

The full case breakdown is provided in Table 3-3.

Table 3-3. Case Matrix.

Type	Case Number	% CH4 in Gas Cloud	% H2 in Gas Cloud	Equivalence Ratio	Volume of Gas Cloud [% Enclosure]	Congestion
Methane Baseline	1.1	100%	0%	1	0.098%	None
	1.2	100%	0%	1	0.098%	A
	1.3	100%	0%	1	0.098%	B
Hydrogen Baseline	2.1	0%	100%	1	0.098%	None
	2.2	0%	100%	1	0.098%	A
	2.3	0%	100%	1	0.098%	B
Equivalence Ratio Sensitivities	3.1	0%	100%	2.5	0.098%	A
	3.2	0%	100%	2	0.098%	A
	3.3	0%	100%	1.5	0.098%	A
	3.4	0%	100%	0.5	0.098%	A
	3.5	0%	100%	0.6	0.098%	A
	3.6	0%	100%	0.7	0.098%	A
	3.7	0%	100%	0.8	0.098%	A
	3.8	0%	100%	0.9	0.098%	A
	3.9	0%	100%	1.1	0.098%	A
Cloud Size Sensitivities	4.1	0%	100%	1	0.030%	A
	4.2	0%	100%	1	0.040%	A
	4.3	0%	100%	1	0.060%	A
	4.4	0%	100%	1	0.080%	A
Mixture Sensitivities	5.1	25%	75%	1	0.040%	A
	5.2	25%	75%	1	0.060%	A
	5.3	25%	75%	1	0.080%	A
	5.4	25%	75%	1	0.098%	A
	5.5	50%	50%	1	0.040%	A
	5.6	50%	50%	1	0.060%	A
	5.7	50%	50%	1	0.080%	A
	5.8	50%	50%	1	0.098%	A
	5.9	75%	25%	1	0.040%	A
	5.10	75%	25%	1	0.060%	A
	5.11	75%	25%	1	0.080%	A
	5.12	75%	25%	1	0.098%	A

3.0 RESULTS & DISCUSSION

3.1 METHANE BASELINE CASES

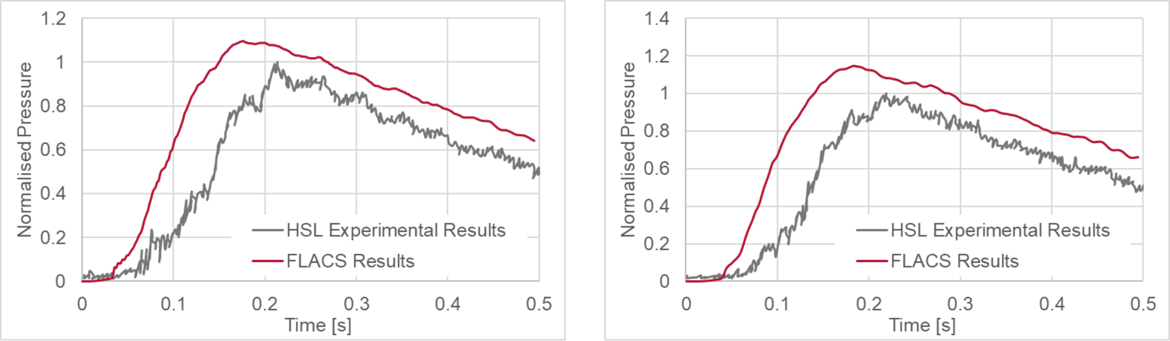
The results from the methane baseline cases are normalized using the peak pressures measured from the equivalent HSE JIP experimental results, to clearly present the level of agreement between the experimental work and the FLACS CFD analysis.

Transient pressures recorded by FLACS CFD at the four pressure transducer locations are shown in Figure 3-1, alongside the results from the equivalent HSE JIP case. The pressures predicted by the FLACS CFD model tend to rise slightly faster and reach slightly larger maximum pressures than the HSE tests, but the overall trends are well represented.

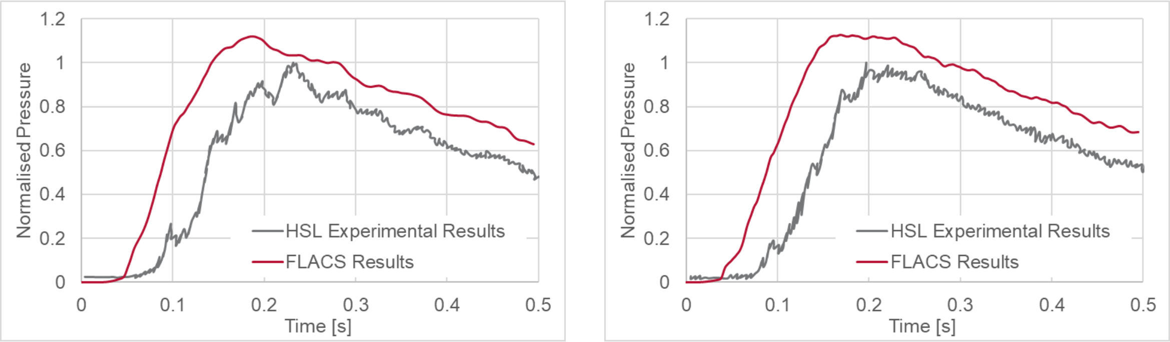
When maximum pressures for Cases 1.1 to 1.3 are examined (Figure 3-2), it is seen that a similar peak pressure is recorded at all pressure transducers for Cases 1.1 (no congestion) and 1.3 (congestion B), showing reasonable agreement with the HSE JIP results. The FLACS CFD model tends to predict a slight overestimate of the peak pressure, giving confidence that the analysis is conservative when compared to the experimental work.

The FLACS CFD results for Case 1.2 (congestion A) show reasonable agreement for PT3 and PT5, but a significant overprediction of pressure at PT2 and PT4. These overpredictions could result from pressure wave reflections from rigid boundaries in the FLACS CFD model (these are damped by wall deflections in reality). Alternatively, as noted earlier, small grid sizes in FLACS CFD (typically less than 20mm) can lead to some artificial generation of turbulence.

In summary, whilst there is some overprediction of pressure at two pressure transducers for Case 1.2, FLACS CFD generally gives good agreement with the HSE JIP experimental results and thus the approach employed is considered suitable for the present work. Although Case 1.2 (i.e. applying Congestion A) has the most significant overprediction of pressure (compared with experimental results), both the experimental and modelling results for this case demonstrate that Congestion A gives the highest overpressures. For this reason, where only one congestion configuration is considered in later cases, Congestion A is used to ensure conservatism.



a) PT2 b) PT3



c) PT4 d) PT5

Figure 3-1. Case 1.1 Transient Results

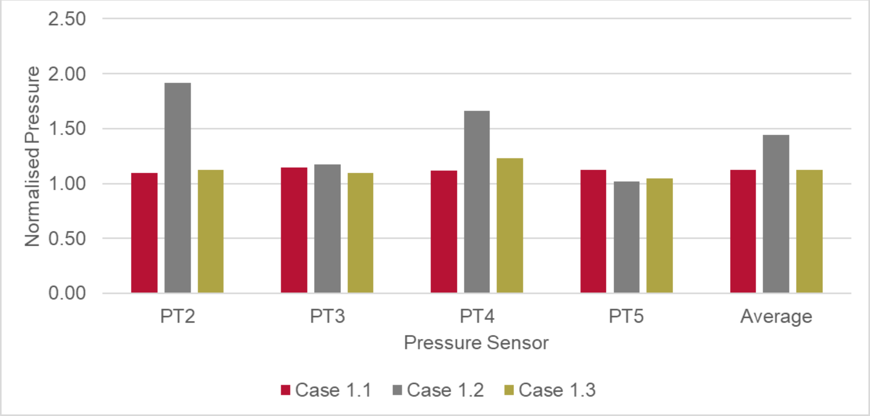


Figure 3-2. Methane baseline results (normalised to experimental results)

3.2 HYDROGEN BASELINE CASES

Hydrogen baseline cases are normalized to the equivalent methane FLACS CFD cases (i.e. Cases 1.1 – 1.3) to allow direct comparison between methane and hydrogen results.

The hydrogen baseline test results are presented in Figure 3-3. For the hydrogen cases, the peak overpressures are generally predicted to be around two to four times higher than methane (dependent on case/transmitter location), indicating that if the existing ISO 21789 criteria is applied then the 10 mbar overpressure criteria would be significantly exceeded. The propensity of hydrogen explosions to generate higher pressures compared to methane explosions has been widely studied elsewhere [4] [5] and is typically attributed to a number of specific hydrogen properties, such as low ignition energy and high flame front velocity.

When comparing Case 2.1 (no congestion) with Cases 2.2 and 2.3 (Congestion A and B respectively), it is noted that Case 2.2 and 2.3 have higher normalized overpressures than Case 2.1, indicating that the ratio between methane and hydrogen overpressures is higher when congestion is considered. This may be due to the congestion increasing the severity of the hydrogen explosion more than the methane explosion.

The highest overpressures for both the hydrogen and methane cases are seen with Congestion A, so this is used for all subsequent cases.

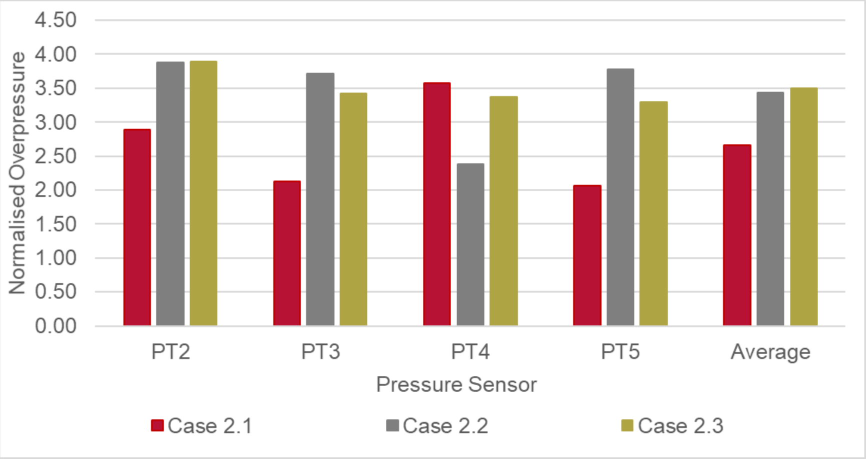


Figure 3-3. Overpressures for hydrogen stoichiometric clouds (normalised to methane overpressures in equivalent geometries).

3.3 EQUIVALENCE RATIOS

ISO 21789 currently defines the maximum allowable gas cloud size in terms of a stoichiometric cloud. For methane a stoichiometric gas cloud typically leads to the highest overpressure (when compared to explosions with differing concentrations of methane/air) [7]. To ensure that a stoichiometric cloud is still the correct basis when using hydrogen, Cases 3.1-3.9 consider a range of equivalence ratios (ER) to identify at what ER the maximum pressure occurs.

These cases are presented in Figure 3-4. While the average peak overpressure across all four pressure transducers occurs with an Equivalence Ratio of 2, this overpressure is only slightly higher than the overpressure seen with an ER of 1 (despite the fact that there is twice as much hydrogen in the case with an ER of 2). The peak overpressure reduces rapidly for ER values less than 1.

The basis of safety in a gas turbine enclosure relies on gas clouds in excess of 0.1% of enclosure volume being detectable. Gas clouds at a high ER typically would exist when there is a greater quantity of gas within the enclosure, and as a result would be more easily detected. As cases with a higher ER are easier to detect within a gas turbine enclosure and the overpressure is only slightly higher for the case with an ER of 2, it is conservative to continue using an ER of 1, as this delivers a similar overpressure despite being less detectable.

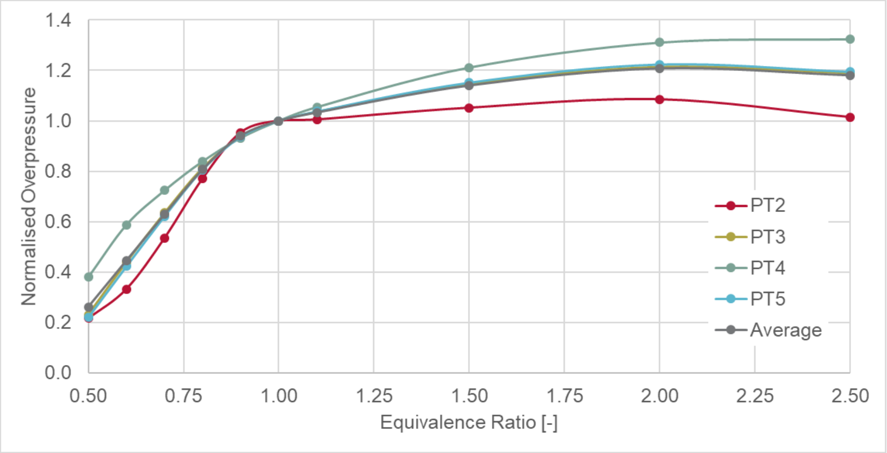


Figure 3-4. Overpressures for Hydrogen Cases at a range of Equivalence Ratios (normalised to ER=1 overpressures).

3.4 CLOUD SIZE ASSESSMENT

Cases 4.1 to 4.4 consider a range of different stoichiometric hydrogen cloud sizes to identify the impact of cloud size on the average maximum pressure (i.e. the average of the maximum pressure recorded at each pressure transducer) within the enclosure (using Congestion A). These results are normalised to Case 1.2 (methane case, congestion A).

The smallest cloud size considered is 0.03% of the enclosure volume, as this is the smallest cloud size that can be assessed using FLACS CFD (due to limitations on minimum grid cell size). The results show a linear relationship (Figure 3-5). Through extrapolation of this trend, the cloud size required to match the methane results (i.e. a normalised overpressure of 1) is estimated at 0.022% of enclosure volume.

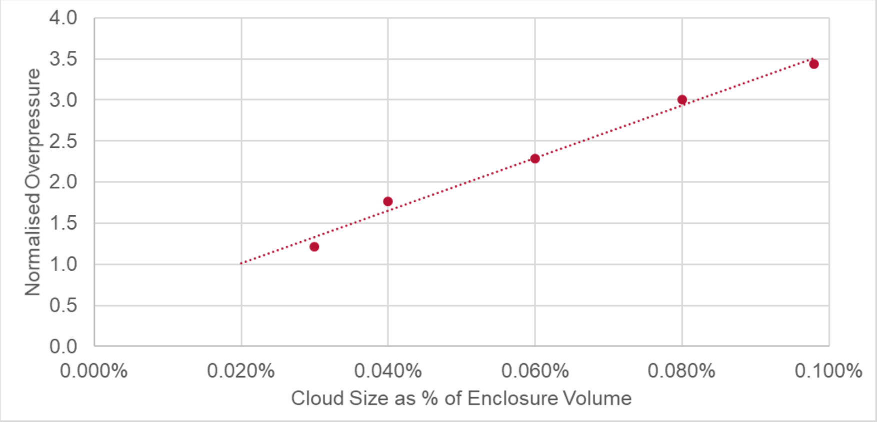


Figure 3-5: Average Overpressures for Hydrogen Deflagration at a range of Cloud Sizes (normalised to Case 1.2)

ISO 21789 requires that the flammable gas in the enclosure must be detectable if it exceeds an equivalent stoichiometric volume of 0.1% of the enclosure volume. In practise, during a leak scenario, gas will be at a range of concentrations throughout the enclosure, therefore it is more useful to consider the total amount of gas within the flammable cloud.

As hydrogen has a significantly smaller stoichiometric air-fuel ratio than methane (2.4:1 and 9.5:1 respectively by volume), a stoichiometric gas cloud of hydrogen requires approximately 4 times as much fuel as an equivalent sized cloud of methane. Compared to methane, this indicates that whilst the overall stoichiometric gas cloud size will need to be much smaller when operating with hydrogen, the total amount of released gas in the enclosure (and as such, detectability) is likely to be broadly similar.

3.5 HYDROGEN/METHANE MIXTURES

Maximum normalised overpressures for a range of cloud sizes and hydrogen/methane blends (Cases 5.1 to 5.12) are presented in Figure 3-6. As the blend increases in hydrogen content (and decreases in methane content), the average maximum overpressures recorded at the pressure transducers increase. It is noted that this is consistent with the conclusions from stoichiometric hydrogen cases (Case 2.1-2.3).

Considering the differing stoichiometric ratios for hydrogen and methane, and the linear trend between pressure and hydrogen content (in Figure 3-6) it is apparent that blends do not present specific issues in terms of cloud size criteria and detectability when compared with pure hydrogen cases. It is however worth noting that existing methane detectors cannot detect hydrogen so for mixtures will be required to operate at a lower threshold methane concentration (since the methane is effectively diluted by hydrogen in the blended cases). With increasing proportions of hydrogen in the fuel detection will become impractical without installing new hydrogen specific detectors.

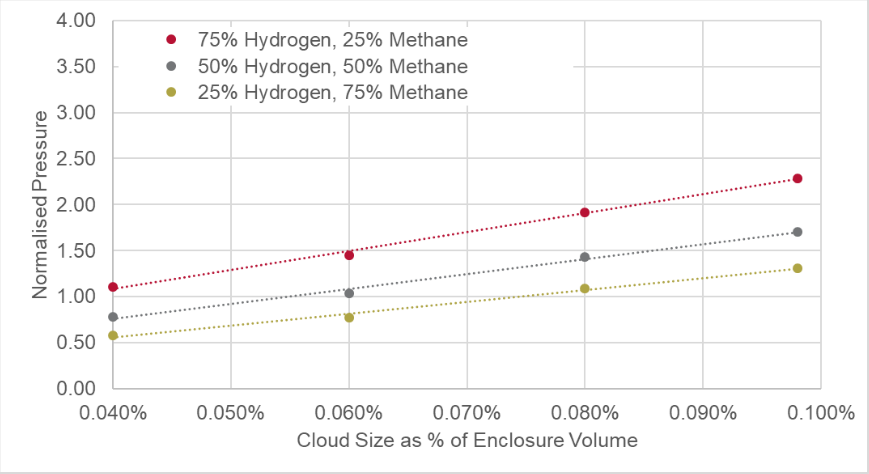


Figure 3-6. Average Overpressure for a Range of Hydrogen/Methane Blends (normalised to Case 1.2)

4.0 CONCLUSIONS AND FURTHER WORK

4.1 CONCLUSIONS

ISO 21789 defines a clear criterion for dilution ventilation in gas turbines, based on a series of experiments carried out by a HSE JIP [3]. These experiments considered gas turbines operating on methane as a fuel.

A numerical assessment of the applicability of ISO 21789 to gas turbines operating on hydrogen has been performed. It is concluded that:

- The analysis has been performed using a modelling tool (FLACS CFD) that is typically used for larger gas cloud explosions. However, using a set of methane baseline cases, reasonable agreement is shown against experimental data measured during the HSE JIP.
- Analysis of hydrogen explosions using the ISO 21789 criteria of a stoichiometric gas cloud equal to 0.1% of enclosure volume lead to significantly higher overpressures than methane explosions of an equivalent volume;
- To meet the 10 mbar explosion overpressure criteria expressed in ISO 21789, analysis indicates that a maximum stoichiometric gas cloud of 0.022% of the enclosure volume would be required when operating with hydrogen;

- When different blends of methane and hydrogen are used, the maximum gas cloud size scales linearly between 0.022% and 0.1% of enclosure volume. These cloud sizes equate to broadly consistent overall quantities of gas when the different stoichiometric ratios of hydrogen and methane and considered. This indicates that detectability of hydrogen and hydrogen/methane blends are likely to be broadly similar.

4.2 FUTURE WORK

This paper describes an approach carried out to ascertain likely gas cloud criteria for gas turbine enclosures operating with hydrogen, and indicates that significantly smaller gas cloud criteria are to be expected. The paper does not set out to specify a new criteria applicable to all enclosures.

It is likely that as hydrogen becomes a more commonplace fuel for gas turbines, ISO 21789 will need to be updated to take account of this. Whilst the present paper indicates the impacts of using hydrogen fuels, it is anticipated that a detailed program of work would be needed to produce formal criteria for acceptable gas cloud sizes in gas turbine enclosures for general use.

5.0 ACKNOWLEDGEMENTS

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