Assessment of Enclosure Ventilation Safety for Hydrogen Fuelled Gas Turbines

Daniel Miles, Frazer-Nash Consultancy, Narrow Quay House, Bristol, BS1 4QA, UK. d.miles@fnc.co.uk

Tristan Vye, Frazer-Nash Consultancy, Narrow Quay House, Bristol, BS1 4QA, UK. t.vye@fnc.co.uk

Aidan Wimshurst, Frazer-Nash Consultancy, Narrow Quay House, Bristol, BS1 4QA, UK. a.wimshurst@fnc.co.uk

Gas turbines are utilised across a wide range of applications, from industrial scale combined heat and power (CHP) stations to smaller units that power remote facilities, such as offshore platforms. Gas turbine manufacturers, packagers and operators are becoming increasingly interested in using hydrogen as fuel, rather than methane. Using hydrogen as a fuel potentially offers a method of reducing carbon dioxide emissions from the gas turbine.

Gas turbines are normally housed within an acoustic enclosure. These enclosures contain a large amount of fuel piping which has the potential to leak and form gas clouds (potentially leading to fire/explosion). ISO 21789 (Gas Turbine Applications - Safety) defines a threshold gas cloud volume, above which all leaked gas clouds must be detectable. This threshold was determined through identifying a volume of gas which, when ignited, led to an overpressure of 10 mbar. As equivalent sized hydrogen gas clouds can generate higher overpressures than methane, the threshold volume in ISO 21789 is not considered valid for hydrogen.

This paper explores the implications for enclosure safety when operating gas turbines on hydrogen, and presents a method of demonstrating adherence to the principles of ISO 21789. The approach replicates the original experimental work carried out by a HSE JIP for hydrogen, using a computational modelling tool (FLACS CFD). This assessment of explosion overpressures is used to define a new threshold cloud volume for hydrogen and hydrogen/methane blends. This modelling work shows that operating with hydrogen can lead to significantly higher overpressures unless the threshold volume is reduced. The impact of reduced threshold volumes on detection strategies is explored through a dilution ventilation analysis, using Computational Fluid Dynamics (CFD).

Introduction

Hydrogen Properties

Hydrogen is currently being investigated as a fuel for gas turbines by multiple OEMs (original equipment manufacturers) to mitigate direct carbon dioxide emissions from the gas turbine. There are several challenges associated with changing fuel types from natural gas to hydrogen, including how safe operation of the turbine within an enclosure is ensured.

Hydrogen has a number of properties that differ significantly from methane and impact the level of hazard associated with the fuel. These differences include:

- Higher propensity to leak from piping – due to hydrogen's small molecular size and high sonic velocity, leaks are more likely to occur.
- Low ignition energy – hydrogen has a low ignition energy compared to methane, although this is unlikely to make a significant difference to enclosure safety, as hot turbine surfaces can ignite both methane and hydrogen.
- Higher overpressures – a number of previous investigations (e.g. (Lowesmith, et al., 2009) (Ma, et al., 2015)) identify that hydrogen typically generates a greater overpressure on ignition than equivalent methane gas clouds.
- Different density – hydrogen has a lower density than methane and is typically buoyant on release into air, whereas methane often sinks on release into air. This in turn affects where the flammable gas clouds will form within an enclosure.
- Hydrogen has a negative Joule-Thompson coefficient at most turbine operating conditions – when hydrogen leaks into the enclosure its temperature increases as it expands, although at typical fuel supply pressures, this temperature rise is only likely to be a few degrees. In contrast, the temperature of methane decreases as it expands because it has a positive Joule-Thompson coefficient.

ISO 21789 Requirements

The differences between hydrogen and methane presented above challenge the industry standard approach to gas turbine enclosure safety, which is laid out in ISO 21789 (Gas Turbine Applications – Safety) (ISO, 2009). The guidance set out in ISO 21789 includes the use of dilution ventilation to prevent the build-up of large flammable gas clouds, as a typical ATEX approach cannot be followed due to the hot turbine surfaces. Section 5.16.5.3.3 of the standard recommends the use of Computational Fluid Dynamics (CFD) to demonstrate ventilation and detection arrangements in the enclosure are suitable:

'Computational fluid dynamics (CFD) modelling or other quantifiable techniques shall be used to validate dilution ventilation in accordance with 5.16.5.3.2 to ensure adequate dilution of a leak is achieved. The modelling shall show that the leak cloud volume at the 100% LEL contour arising from the leak that can cause a gas turbine trip based on gas detection trip settings in the ventilation outlet ducts, converted to an equivalent volume at stoichiometric concentration, shall be no larger than 0.1% of the net volume of the enclosure.'

The selection of 0.1% of enclosure volume as the defined limit for undetectable flammable gas clouds is derived from a series of experiments carried out by a HSE JIP (Ivings, et al., 2004). It was identified that a natural gas cloud of this volume would lead to an enclosure overpressure less than 10 mbar, which was defined as a typical limit above which there is a risk to personnel and plant outside of the enclosure.

The HSE JIP tests involved igniting clouds of natural gas in a representative enclosure and measuring the pressure. As hydrogen typically generates a greater overpressure on ignition than methane, a gas cloud of 0.1% of enclosure volume will lead to an overpressure in excess of the 10 mbar limit. The quantitative safety criteria currently defined in ISO 21789 is therefore not suitable for gas turbines operating on hydrogen or hydrogen/methane blends. However the principle of the approach remains valid.

This paper discusses an approach that could be used to overcome the limitations of the current safety standards for hydrogen fuel applications. A combination of explosion modelling and CFD analysis are proposed as part of a risk-based approach which aims to provide a practical solution for gas detection systems whilst maintaining the safety principles and 10 mbar overpressure criteria of the existing standards. The approach consists of the following steps:

1. Validation of modelling tool (FLACS CFD) against existing data from HSE JIP experimental program.
2. Assessment of overpressures likely to be generated by hydrogen explosions, when using existing ISO 21789 criteria.
3. Identification of new limiting cloud volume for hydrogen, required to maintain 10 mbar overpressure criteria.
4. Ventilation assessment of a methane release using CFD to ascertain detector location/set point requirements to allow detection of all releases leading to gas clouds in excess of the 0.1% of enclosure volume criteria specified in ISO 21789.
5. Ventilation assessment of a hydrogen release using CFD to ascertain detector location/set point requirements to allow detection of all releases leading to gas clouds in excess of the new limiting gas cloud volume identified in Step (3).

In the present paper, the stages described above have been carried out to demonstrate the proposed approach for an acoustic enclosure that is currently operating using a methane-based fuel, and is being upgraded for use with hydrogen.

Step 1: Validation of Explosion Modelling Tool

Background

The HSE JIP testing program utilised an enclosure with representative congestion, consisting of a number of small-bore piping items configured in a cube format (see Figure 1 for an example of congestion used). The congested zone was filled with a flammable (stoichiometric) gas cloud which was ignited. Pressure transmitters on the wall recorded transient pressure profiles, which were used to identify the peak overpressure at the enclosure wall.

The testing considered a number of different sensitivities, including:

- Different enclosure volumes.
- Different congestion configurations (spacing between the 'piping' items).
- Steady state gas release vs quiescent.
- Different gas cloud sizes.

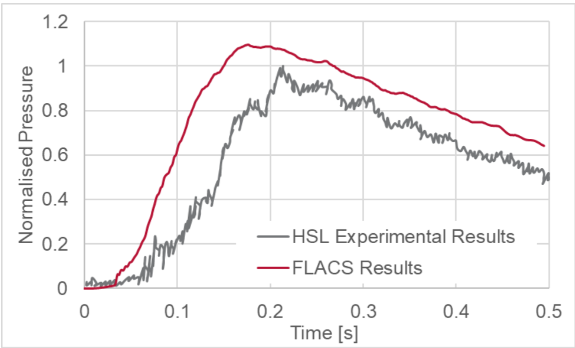
The assessment identified that a gas cloud of 0.1% of enclosure volume led to overpressures of less than 10 mbar for all sensitivities. This result forms the basis for the limit defined in ISO 21789.

Figure 1: HSE JIP Testing Congestion

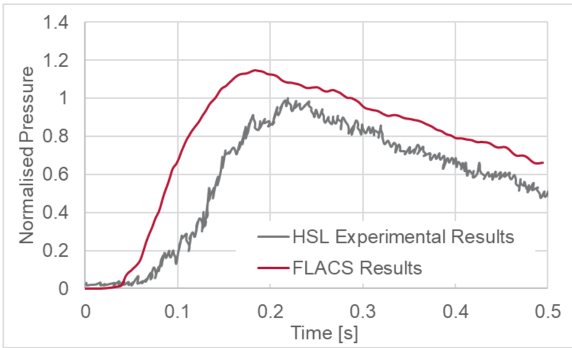
Validation of FLACS CFD (for Assessment of Enclosure Overpressure)

The HSE JIP testing was replicated in FLACS CFD to determine the equivalent overpressure when operating with hydrogen or hydrogen/methane blends, and to identify a limiting gas cloud size for a specific case. This work is described in detail in an earlier paper (Vye & Miles, 2021) and the key results are summarised below.

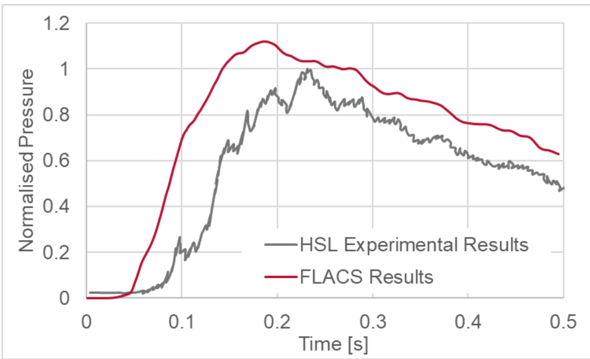
The initial phase of the FLACS CFD modelling compared FLACS CFD results to those from the HSE JIP experimental work, considering methane gas clouds. Normalised results for this are presented in Figure 2. As can be seen from this figure, the model results closely match the experimental results from the HSE JIP, with a slight overprediction. This overprediction gives some confidence that the present computational approach is likely to provide conservative pressure predictions.



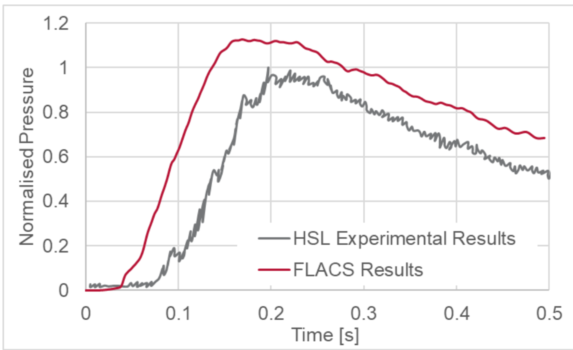
a) PT2



b) PT3



c) PT4



d) PT5

Figure 2: Normalised Transient Pressure Profiles for HSE JIP project and FLACS Modelling at a range of Pressure Transmitter (PT) Locations

Step 2: Hydrogen Overpressure Assessment

Following the assessment of the suitability of FLACS CFD for modelling small explosions within an enclosure, the assessment was repeated considering hydrogen as the fuel. The geometry, congestion configuration and cloud sizes were kept consistent with the methane cases, and the results are presented in Figure 3, which shows the peak overpressure at each pressure transmitter, normalised to the equivalent overpressure for methane cases. Results for three different cases are shown, which correspond to differing congestion configurations.

Figure 3 shows that the computational model calculates hydrogen overpressures that are up to four times higher than the overpressures from an equivalent cloud of pure methane. As expected, this shows that hydrogen overpressures are significantly higher than methane overpressures for an equivalent cloud volume and the existing 0.1% enclosure volume criteria is not suitable for use when operating with hydrogen.

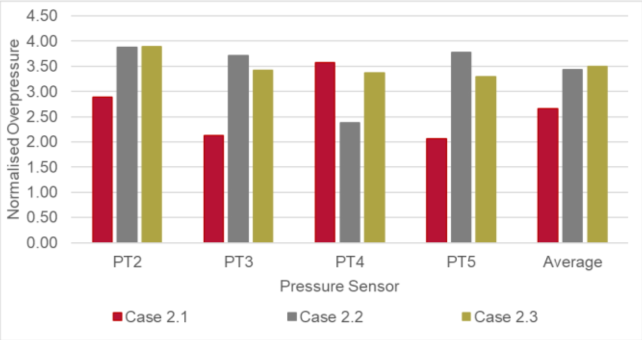


Figure 3: Initial Hydrogen Explosion Modelling Results

Step 3: Identification of a New Limiting Cloud Volume for Hydrogen

In addition to comparing equivalent clouds of pure hydrogen with pure methane, a range of gas cloud sizes and fuel compositions (i.e. differing hydrogen/methane blends) were investigated with the FLACS CFD model. These calculations allowed limiting gas cloud sizes to be identified for differing blends of methane and hydrogen, which could then be used for dispersion and ventilation modelling. Figure 4 shows gas cloud sizes for a range of hydrogen/methane blends, normalised to the cloud size defined in ISO 21789. It should be noted that the limiting cloud volume in Figure 4 is not necessarily applicable to other gas turbine enclosures, as the effects of enclosure volume and congestion have yet to be investigated.

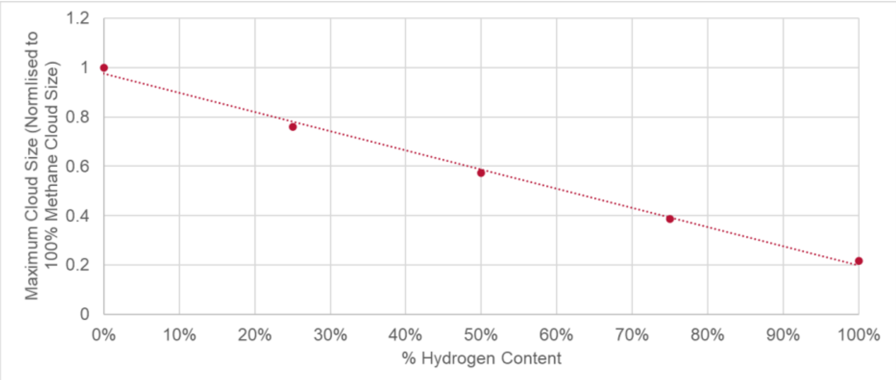


Figure 4: Limiting Cloud Sizes used for Dispersion Modelling

The explosion modelling results indicate that for the existing enclosure overpressure safety criteria to be retained, the maximum allowable volume of a hydrogen gas cloud resulting from a leak should be around 5 times smaller than that for methane. Gas leaks resulting in larger gas clouds should initiate an automatic trip of the gas turbine following leak detection by gas detectors.

Implications for Gas Turbine Safety Assessments

Whilst Figure 4 suggests that significant reductions in the gas detector trip thresholds may be required, some benefit is gained from further examination of the safety criteria. For methane, the maximum gas cloud size is specified as an equivalent stoichiometric volume. The stochiometric air-fuel ratio of hydrogen (2.4) is considerably lower than the stochiometric air-fuel ratio of methane (9.6), so the proportion of hydrogen within a stochiometric cloud is higher than for methane. As the difference in the hydrogen and methane overpressures is similar to the difference in the air-fuel ratios, it follows that the volume of hydrogen in the enclosure, at the limiting gas cloud volume, is actually similar to that for methane. Gas detector settings for hydrogen can therefore be expected to be reasonably similar to those for methane, despite the differences in their explosion characteristics. This provides some confidence that a broadly similar ventilation analysis methodology and gas detection approach can be retained for hydrogen fuels.

In line with the assessment approach currently used for methane, detailed analysis of the dilution and dispersion of gas from the leak site is still required to confirm the adequacy of the ventilation and gas detection systems. These differences in the dilution and dispersion of gas from the leak site are investigated later, in Step 4 and 5 of the present work. It is expected that the differences in the gas cloud properties, buoyancy characteristics and the momentum of the gas jet will result in different dispersion behaviour. For example, the density of hydrogen is approximately 9 times lower than the density of natural gas, based on a typical gas natural gas composition and enclosure temperature. The mass of hydrogen contained within a limiting stochiometric cloud is likely to be an order of magnitude lower than the mass of natural gas contained within an equivalent natural gas cloud. It follows that the leak mass flow rate needed to generate such a limiting stoichiometric cloud would be an order of magnitude lower for hydrogen than for natural gas. In the present work, the fuel pressures for hydrogen and methane are equal, and the momentum of the hydrogen jet from the leak site is considerably lower than for a natural gas leak. This is expected to result in the hydrogen leaks being more strongly advected by the ventilation flow than the corresponding methane leaks (and this will be shown to the case later in Step 4 and 5 of the present work).

Assuming the gas leak flow at the leak site is choked, the reduced mass flow rate for hydrogen (as mentioned above) is linked to a smaller cross-sectional area of the leak hole. Current guidance suggests that leak areas between 0.25 mm^2 and 25mm^2 should be considered (Ivings, et al., 2004). As leak areas for hydrogen are expected to be smaller, they may fall outside of this range. Considering this and the higher leak propensity of hydrogen, the current guidance on leak sizes may need to be revisited for hydrogen, to consider smaller leaks.

As a result of these physical differences between leaks of natural gas and hydrogen, and the different gas cloud volume criteria identified from the explosion modelling, it is clear that dispersion modelling must be revisited for hydrogen, even where existing analysis has been completed for methane on a given enclosure. This analysis may result in different gas detector locations being identified and different trip settings. Noting that the infra-red gas detectors which are typically used for natural gas are unable to detect hydrogen, this analysis can be completed as part of the design for new gas detection systems.

Step 4: Ventilation Assessment of Methane Releases using CFD

This step assesses the dispersion of methane gas leaks by the ventilation flow within the specific gas turbine enclosure under consideration. Computational Fluid Dynamics (CFD) is used to demonstrate that gas leaks resulting in a steady-state gas cloud larger than the defined maximum will be detected by gas detectors at the ventilation outlet due to dispersion by the ventilation flow. In practise, this is achieved by simulating a number of postulated worst case gas leak scenarios, with gas clouds at the limiting value, and demonstrating that the gas concentrations at the outlet are high enough for reliable detection to be achieved. Suitable gas detector settings which are high enough to avoid spurious actuations but low enough to ensure safe shutdown of the gas turbine in the event of a leak can then be defined.

This analysis was completed in collaboration with Centrax Gas Turbines for a gas turbine enclosure that is being converted for hydrogen fuels, as part of the HYFLEXPOWER hydrogen demonstrator project. A CFD model of the gas turbine enclosure was setup and solved using ANSYS Fluent. The model was solved using a two-species steady state analysis, with full buoyancy effects and the local mixture density calculated using the ideal gas law. The leak was represented by a mass, momentum and energy source, applied to a small volume at the leak site. The momentum of the jet was calculated using the choked flow area, venting at Mach 1 from the fuel supply line conditions and the k-ε turbulence model was used to model the turbulence generated by the jet. This approach is consistent with the CFD best practise guidelines defined by the HSE JIP (Ivings, et al., 2004).

Six postulated worst-case gas leak locations and directions were considered. An initial ventilation only CFD analysis was performed to inform the selection of the worst-case leak scenarios, on the basis of low velocity regions in proximity to the fuel supply pipework, as well as the distance from the ventilation outlet.

Step 5: Ventilation Assessment of Hydrogen Releases using CFD

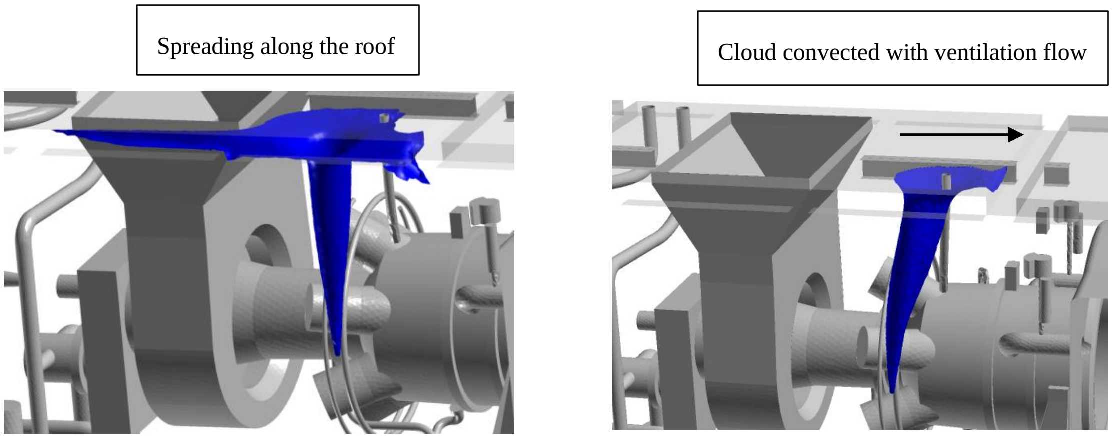
Whilst this industry standard process for methane-based fuels essentially remains the same for hydrogen fuel, a number of modifications were made to the approach to account for the different properties of the two fuels:

- The material properties of the simulated gas (density, dynamic viscosity, thermal conductivity and ratio of specific heats) were changed from those of 100% natural gas to 100% hydrogen.
- The maximum permissible stochiometric cloud volume was reduced by a factor of 5 (following the insights from the explosion modelling presented in Step 3 above) to account for the increased overpressure in the event of ignition of the gas cloud.
- The Lower Explosive Limit (LEL) of the simulated gas was changed to that of hydrogen. This change was found to be small, as hydrogen and methane have similar LELs.

The same leak locations and directions were adopted for hydrogen, to facilitate a direct comparison between the hydrogen and natural gas results.

Results

Figure 5 shows an iso-surface of gas concentration that corresponds with the LEL for the gas, from a leak originating from the side of the fuel ring. The iso-surface surrounds a region that represents the stochiometric cloud volume and is useful to visualise the shape of the gas cloud.

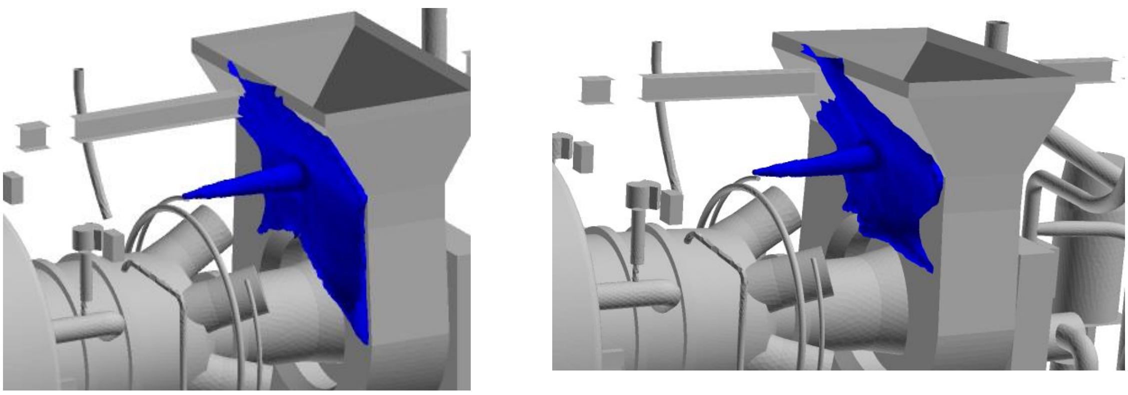


(a) 100% Natural Gas (b) 100% Hydrogen

Figure 5: Iso-surface of 100% LEL for leaks of 100% natural gas and 100% hydrogen, originating from the port side of the fuel ring. The roof of the enclosure and the side walls have been made transparent to improve visibility.

Overall, the shape of the natural gas cloud and the hydrogen cloud are similar. Both clouds take the shape of an expanding jet and spread out on contact with the roof of the enclosure. However, there are some noticeable differences in the shape of the clouds. The hydrogen jet has a lower momentum than the natural gas jet, due to the lower leak mass flow rate and overall mass of hydrogen in the enclosure. The lower momentum results in the hydrogen cloud being increasingly advected by the ventilation flow towards the ventilation outlet, noticeably changing the shape of the cloud.

When the jet impacts the roof of the enclosure, the hydrogen cloud shows less spreading along the roof than the natural gas cloud. This is due to the lower momentum of the hydrogen jet and also the lower mass of hydrogen in the enclosure (the hydrogen cloud itself is smaller than the natural gas cloud). While it might be expected that the hydrogen cloud would show greater spreading along the roof than the natural gas cloud due to its greater mass diffusion coefficient, this is not found to be the case, as the shape of the cloud is dominated by the momentum of the jet and the mass of hydrogen in the enclosure.



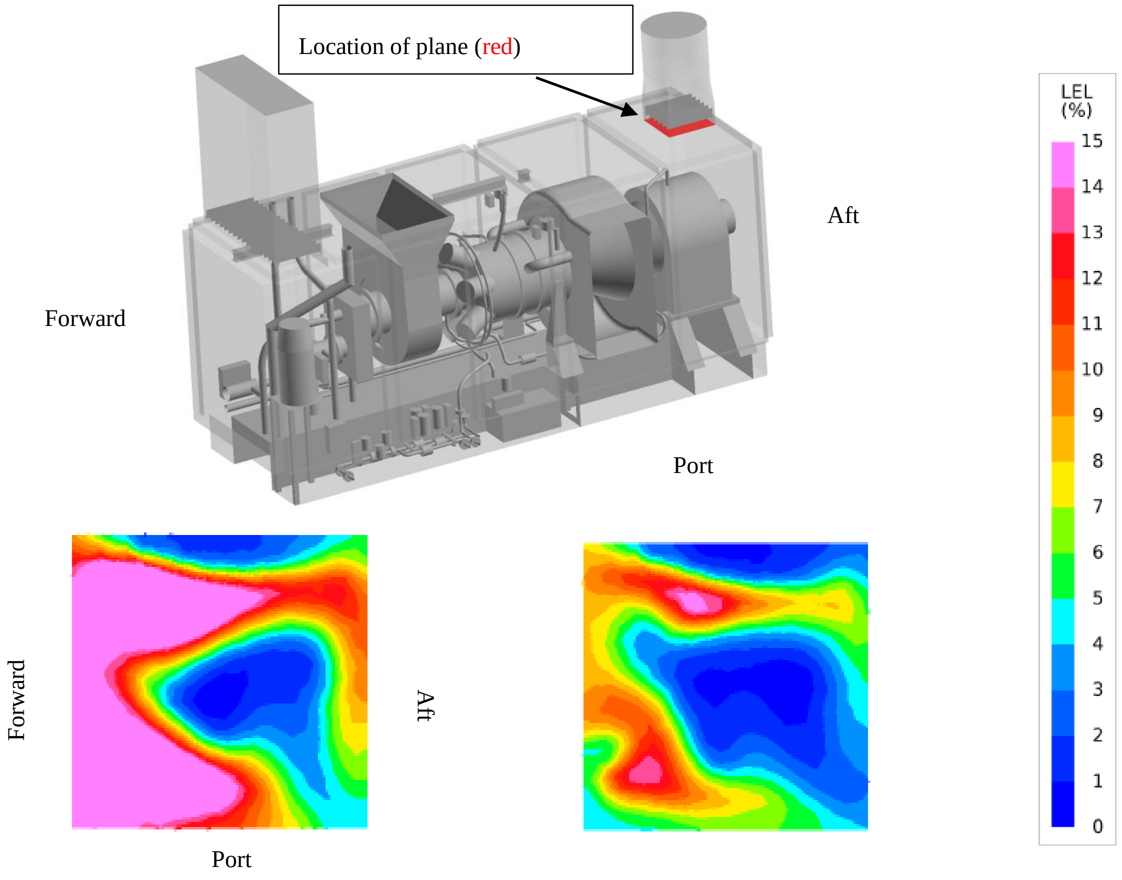
(a) 100% Natural Gas (b) 100% Hydrogen

Figure 6: Iso-surface of 100% LEL for leaks of 100% natural gas and 100% hydrogen, originating from the top of the fuel ring.

Figure 6 shows an iso-surface of 100% LEL for a leak originating at the top of the fuel ring. For this leak scenario, the gas jet travels forward and expands, before impacting the gas turbine air intake. The shape of the clouds of natural gas and hydrogen are more similar than the previous leak scenario (shown in Figure 5). However, the same qualitative differences in the shape of the natural gas and hydrogen clouds can still be observed.

The hydrogen cloud shows less spreading along the surface of the gas turbine air intake than the natural gas cloud, due to the lower momentum of the hydrogen jet and the lower mass of hydrogen in the enclosure. For this leak scenario, the hydrogen cloud does not appear to drift significantly towards the ventilation outlet. This is because the ventilation flow behind the gas turbine air intake is relatively slow moving, and therefore the gas cloud is relatively undisturbed by the ventilation flow.

The differences observed in the natural gas and hydrogen gas cloud shapes are sufficiently small that it may be possible to use a similar gas detection strategy when the gas turbine is upgraded from a methane-based fuel to hydrogen fuel. To specify an appropriate layout and trip settings for the gas detectors, the gas concentration in the vicinity of the proposed detectors needs to be considered.



(a) 100% Natural Gas (b) 100% Hydrogen

Figure 7: Contours of % LEL on a horizontal plane through the aperture of the ventilation outlet.

Figure 7 shows contours of gas volume fraction on a horizontal plane in the aperture of the ventilation outlet duct, where the gas detectors are likely to be installed. The volume fraction contours have been expressed as a percentage of the LEL, where a value of 100% indicates that the volume fraction is equal to the LEL for the gas. It should be noted that the LEL for hydrogen is 4.0% by volume, which is slightly lower than the LEL for methane (4.4% by volume). Therefore, when making direct comparisons between the hydrogen and natural gas results, the concentration of hydrogen is slightly lower at the same percentage of the LEL.

The contours in Figure 7 show that the distribution of hydrogen in the ventilation outlet is sufficiently similar to that of natural gas that the gas detectors can be installed in the same location when the engine fuel supply is switched from 100% natural gas to 100% hydrogen. In practice, this means that (for this enclosure) the methane gas detectors could be directly replaced with hydrogen detectors, or hydrogen detectors could be installed alongside the methane detectors. However, despite the similarity in the gas distribution, the local concentration of hydrogen is significantly lower than that of natural gas. Therefore, the trip settings on the hydrogen detectors will need to be chosen carefully, to ensure that the maximum permissible hydrogen cloud size is detected whilst also avoiding spurious actuation.

Conclusions

In its current form, the requirements set out in ISO 21789 are not directly applicable to gas turbine enclosures where the fuel supply contains a significant proportion of hydrogen. The primary reason for this is that in the event of ignition, the maximum overpressure from a gas cloud that contains hydrogen is higher than an equivalent gas cloud of pure methane or natural gas.

The present paper has presented an approach for assessing the enclosure ventilation safety of gas turbines operating on hydrogen fuel. This approach has five main steps:

1. Validation of a modelling tool (FLACS CFD) against experimental data from the HSE JIP experimental programme.
2. Assessment of overpressures likely to be generated by hydrogen explosions, when using existing ISO 21789 criteria.
3. Identification of new limiting cloud volume for hydrogen, required to maintain 10 mbar overpressure criteria.
4. Ventilation assessment of a methane release using CFD to ascertain detector location/set point requirements to allow detection of all releases leading to gas clouds in excess of the 0.1% of enclosure volume criteria specified in ISO 21789.
5. Ventilation assessment of a hydrogen release using CFD to ascertain detector location/set point requirements to allow detection of all releases leading to gas clouds in excess of the new limiting gas cloud volume identified in Step (3).

This approach maintains the principles of the current safety criteria defined in ISO 21789 for methane, by using explosion modelling to specify a maximum allowable gas leak volume for hydrogen. In order to maintain the same overpressure criteria, the maximum allowable cloud volume is reduced for hydrogen compared to methane. The FLACS explosion modelling presented in the present paper predicts that a reduction in the maximum allowable cloud volume of 5 times would be sufficient to maintain the same overpressure criteria. However, this value may not be appropriate for other enclosures as the effects of enclosure volume and congestion have yet to be investigated.

This reduction in maximum permissible stochiometric cloud size has implications for the gas detection system in the enclosure and these implications have been explored using a CFD model of a gas turbine enclosure. The CFD model showed that for the gas leak cases considered, the distribution of hydrogen within the enclosure was similar to the distribution of natural gas. For the gas turbine enclosure considered, it may therefore be possible to safely upgrade the package for operation with hydrogen with only minimal changes to the gas detection system. It is proposed that the requirements set out in ISO 21789 are updated to support operation of gas turbines enclosures using a significant quantity of hydrogen in the fuel supply.

Acknowledgements

We kindly acknowledge Michael Drury and Simon Wortmann from Centrax Gas Turbines for funding the program of work on which this paper is based. We also would like to acknowledge the support provided by Gexcon and our colleagues at Frazer-Nash Consultancy: Irfan Siddiqui, Chloe Sous, Peter Cossins and Tim Houghton for contributing to the study and the review of the paper.

References

ISO, 2009. *Gas Turbine Applications - Safety, ISO 21789:2009(E), First Edition, Section 5.16.5*.

Ivings, M., Lea, C. & H, L., 2004. *Outstanding safety questions concerning the use of gas turbines for power generation: Best practice guidelines for CFD, Issue 1, Health and Safety Executive CM/03/12*.

Lowesmith, B. J., Mumby, C., Hankinson, G. & Puttock, J. S., 2009. *Vented Confined Explosions Involving Methane/Hydrogen Mixtures.*

Ma, Q., Li, D. & Shen, S., 2015. Comparison of explosion characteristics between hydrogen/air and methane/air at the stoichiometric concentrations. *International Journal of Hydrogen Energy,* 40(28).

Vye, T. S. & Miles, D., 2021. Gas Turbine Enclosures: Determining Ventilation Safety Criteria Using Hydrogen Explosion Modelling.