Is ventilation your trustworthy old friend when it comes to hydrogen?

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Hydrogen is poised to become a pillar in the transition towards a more sustainable energy system. As a result, many governments, businesses, and research institutions are looking to use hydrogen as an alternative to natural gas, in particular for power and transport applications (gas turbines, hydrogen fuel cells and hydrogen combustion engines). Although industry has extensive experience in using hydrogen as part of their manufacturing processes, many new applications require hydrogen to be deployed close to the public. However, there seems to be a lack of awareness, particularly among new entrants, of the very different properties and explosion characteristics of hydrogen compared to natural gas. One crucial difference is the difficulty that typical ventilation systems have to dilute a hydrogen leak to concentrations below which no damaging overpressure are expected. In natural gas applications, ventilation is a well-established component of the "basis of safety" in enclosures (compressor shelters, gas turbines). However, when using hydrogen, ventilation alone might not be enough to achieve a non-flammable atmosphere. This paper will present examples of hydrogen leak dispersion in enclosures and the potential explosion overpressures that could be expected. We will show the influence of the size of the gas cloud on the severity of the explosion and the effect of different ventilation arrangements. Possible mitigation strategies will then be presented, to enable the safe deployment of hydrogen in applications that require close proximity to the public.

Keywords: Hydrogen, Ventilation, Dispersion, Explosion, CFD, Computational Fluid Dynamics

Introduction

Hydrogen is expected to play a major role in the transition towards a more sustainable energy system, with numerous projects underway along the entire value chain from production through storage and distribution to a wide variety of end-user applications. As a result, many governments, businesses, and research institutions are looking to use hydrogen as an alternative to natural gas, in particular for power and transport applications (gas turbines, hydrogen fuel cells and hydrogen combustion engines). The safe introduction of hydrogen in novel applications is a pre-requisite if hydrogen is to fulfil its promise in the energy transition; a serious accident would result in the loss of public support and license to operate.

An important challenge for the transition to a "hydrogen economy" is that many new applications require hydrogen to be deployed close to the public, compared to the traditional use of hydrogen in industrial installations (refineries, chemical plants, nuclear plants) where strict safety standards can be applied and only highly trained personnel are in close proximity to the hazard. This is particularly relevant to the use of hydrogen as a passenger vehicle fuel, as the public is expected to refuel their cars (as is done for petrol and diesel cars) and compression and storage installations, handling hydrogen at pressures in the order of 700-900 bar, will be located close to public areas (Figure 1).

This paper presents a ventilation, dispersion and explosion study for a Hydrogen Refuelling Station (HRS). We focus on leaks originating in the compressor used to boost the pressure of the hydrogen prior to refuelling. Because of the low density of hydrogen, it is necessary to compress it to very high pressures (between 700-900 barg) in order to provide sufficient range for a typical passenger car (Pratt *et al.*, 2015; Lin *et al.* 2018). This is considered a high-risk area due to the high pressure and the cyclical nature of the operation. We studied the effect of ventilation rates on the size and reactivity of the gas cloud and its subsequent influence on the severity of the explosion.

Case Study

Figure 1 shows a concept arrangement for a HRS, showing the different elements required to refuel a hydrogen-powered car (Skjold *et al*, 2017).

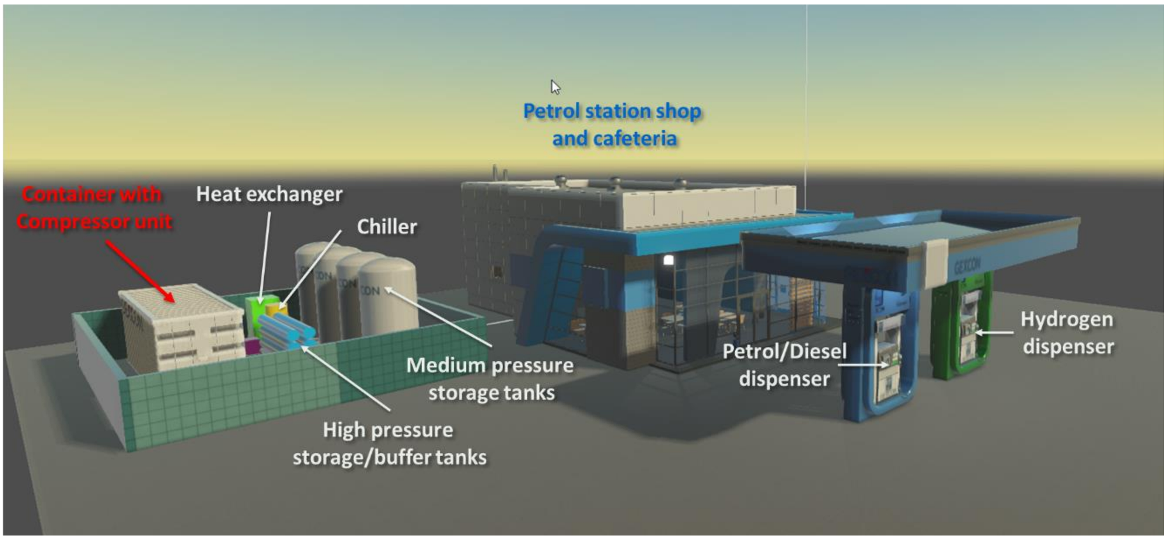


Figure 1. Concept arrangement for a Hydrogen Refuelling Station (HRS).

This picture shows some segregation between the high-pressure compression and storage area and the vehicle forecourt, however in other designs these are closer together. Nevertheless, a hydrogen vapour cloud explosion (VCE), even in this arrangement where the compressor unit is relatively far from the public area, is very likely to have a serious impact in places accessible to the public, like the forecourts and shop. Therefore, it is essential to understand the hazards presented by a leak of hydrogen and the potential consequences in case of an ignition of such a leak.

The focus of this paper are releases of high-pressure hydrogen inside the compressor enclosure. The objective is to understand the size of the potential flammable gas clouds and how mechanical ventilation affects both the total volume of the flammable cloud and the volume of the equivalent stoichiometric gas cloud (Q8), which is often used to calculate the corresponding explosion overpressure in case of ignition (Middha *et al*., 2006; Middha *et al*., 2008).

Link to Hazardous Area Classification

As part of the design process for a facility handling flammable materials, a hazardous area classification (HAC) study should be performed. There are a number of standards and recommended practices (BS-EN-60079-10-1, API RP 505, EI 15) but their overall objective is to identify the areas where flammable atmospheres might exist in order to support the control of ignition sources. The HAC process normally only considers small fugitive leaks (e.g. from flanges, valves, connections) or planned operational releases (e.g. planned venting). For example, BS EN 60079-10-1 considers releases in the order of 0.025 to 2.5 mm^2 (equivalent to hole diameters of 0.2 to 1.8 mm). The hazardous zones determined during the HAC process are not intended to cover more important releases that could lead to a major accident hazard, like the rupture of small-bore piping or a blown gasket in a flange.

For this study, we decided to focus on relatively small leak sizes, in the range typically used to determine the hazardous area classification for a facility, according to international standards. Two hole sizes were selected for this study, 0.1 and 0.5 mm^2, which are in the middle of the range suggested by BS EN 60079-10-1 and represent conditions where the release opening might expand, as is the case for very high-pressure leaks. Table 1 below shows the ventilation velocity required to achieve high dilution and the hazardous area extent calculated according to BS EN 60079-10-1. As the release characteristic calculated intersects the 'high dilution' line above the area plotted in Figure C.1 in the standard, we extrapolated the line to obtain the required ventilation velocity.

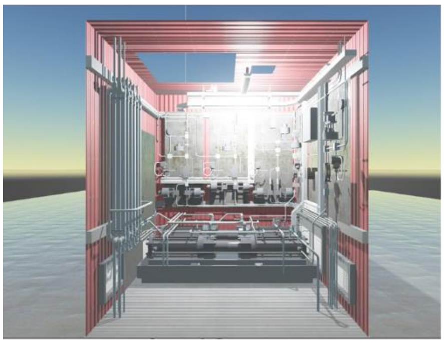
Table 1. Ventilation velocity and hazardous area extent calculated according to BS EN 60079-10-1

Hole Size (mm^2)	Pressure (barg)	Temperature (°C)	Rel. Characteristic (m^3/s)	Ventilation velocity for high dilution (m/s)	Calculated Hazardous Distance (m)
0.1	950	30	1.35	18	3
0.5	950	30	6.74	85	6

It is clear that very high ventilation velocities would be required to achieve high dilution for these releases and "Non-Hazardous zone" (Zone 2 NE) is not achievable. A 3 m zone 2 will cover the whole enclosure, which is reasonable for such a system.

Modelling Study Set-up

A CAD model of the container housing the compressor and hydraulic power unit can be seen in Figure 2. The compressor itself is located in the module to the right. The ventilation system involves 5 air intakes through grilles in the doors and extraction through the roof. The flow rate for the extraction in the original design was 1,000 m^3/h.



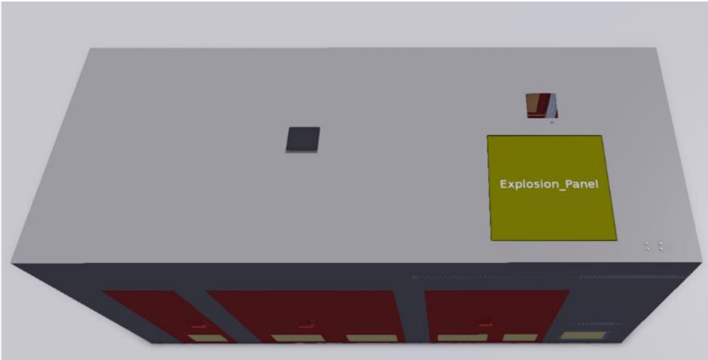


Figure 2. Geometry of the compression module. Internal hydraulic power unit and associated pipework (left) and external view of the container housing the compressor with an explosion relief panel on the roof (right).

The container module was also equipped with an explosion relief panel measuring 1.1m x 1.1m and yielding at 200 mbarg.

The study was performed using FLACS-CFD © (version 22.1), which is a respected and thoroughly validated tool developed for ventilation, dispersion, explosion and fire simulations in complex geometries.

Table 2. Parameters used for FLACS-CFD simulations

Hole Sizes (mm^2)	Pressure (barg)	Temp. (°C)	Leak Duration (s)	Leak direction	Ventilation flow rate (m^3/h)	Vent panel dimensions (m)	Vent panel opening pressure (mbar)
0.1 & 0.5	950	30	30 & 60	Vertical downwards	1000, 1500, 2000, 5000 & 10000	1.1 x 1.1	200

In the compressor module, most leaks are expected to occur in joints and instrument connections associated with the compressor. Figure 3 below shows the location of the leak studied, on the discharge size of the compressor. The leak pointing vertically downwards is likely to represent a worst-case scenario, as the high momentum will be partially destroyed when impacting on the ground, causing the leak to spread and only then start rising towards the extraction point.

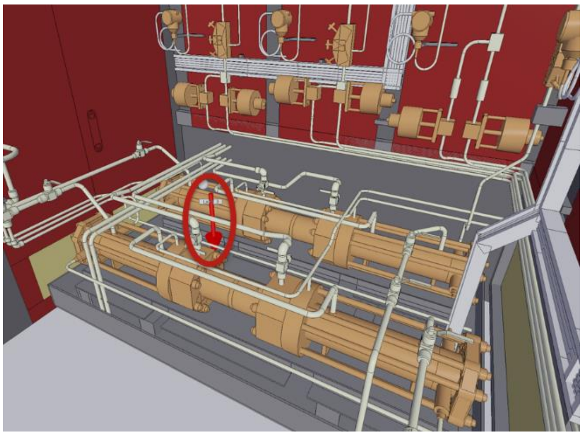


Figure 3. Location and direction of leak inside the compressor module.

Results & Discussion

Ventilation

The first step of the study was to establish the air flow field caused by the ventilation. This is a standard step before dispersion simulations are run. The ventilation was allowed to stabilise before the leak was started. As can be seen in Figure 4, the original ventilation rate (1,000 m^3/h) resulted in air speeds below 0.5 m/s in most of the container. Only around the extraction point higher air speeds were observed. When the ventilation rate is increased to 5,000 m^3/h, air speeds around 2 m/s were achieved, with higher speeds observed around the ventilation grilles and the extraction fan. Only at 10,000 m^3/h the air speed reached high values around the location of potential leaks.

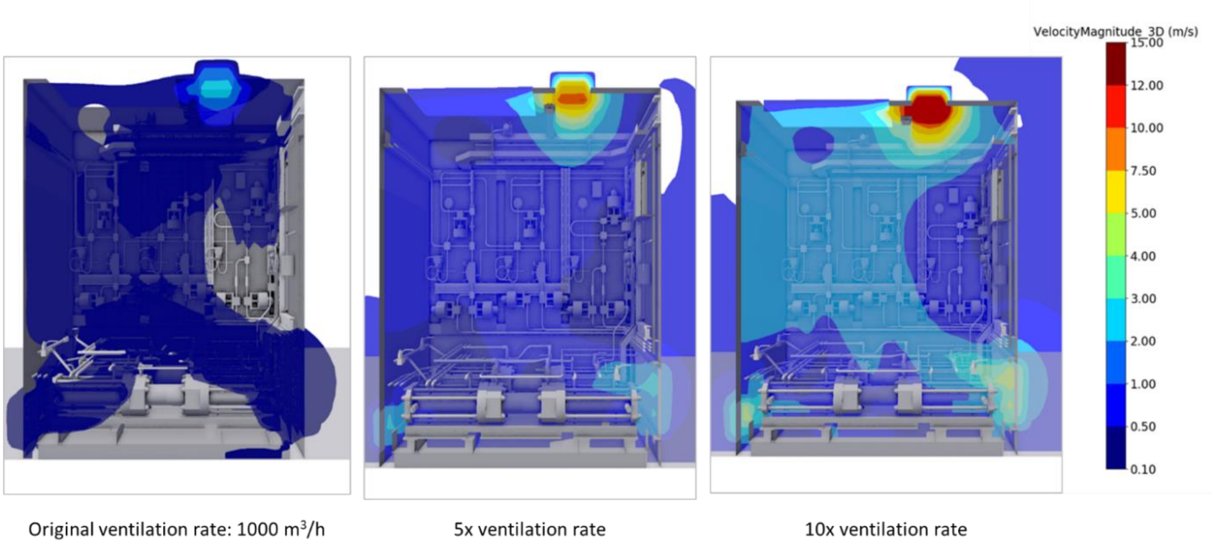


Figure 4. 3D plots showing the velocity magnitude of the airflow before the leak starts.

It must be noted that the very high ventilation rates used in this study are for illustration purposes, with the objective to demonstrate the effect of ventilation on the dispersion of a flammable cloud. It is recognised that such high rates in a small enclosure (5,000 m^3/h would be equivalent to 300 Air Changes per Hour) would be unpractical in real applications.

Maybe more importantly, this study demonstrates that the configuration of the ventilation system needs to be optimised, as in the current configuration (inlet at the bottom and extraction at the top) high air speeds were only achieved close to the inlet/ outlet points. A ventilation system including local extraction close to the points where leaks are expected (additional to background ventilation) could potentially improve the overall air movement and thus reduce the accumulation of flammable gases in enclosures where very high-pressure hydrogen is handled.

Dispersion

After the ventilation had stabilised, the hydrogen leak was started and it was allowed to continue for 30 seconds. Figure 5 shows the variation of the total volume of the flammable cloud (volume of gas between Lower Flammability Level - LFL and Upper Flammability Level - UFL) as a function of time for the different ventilation rates studied for a 0.1 mm^2 leak lasting 30 s.

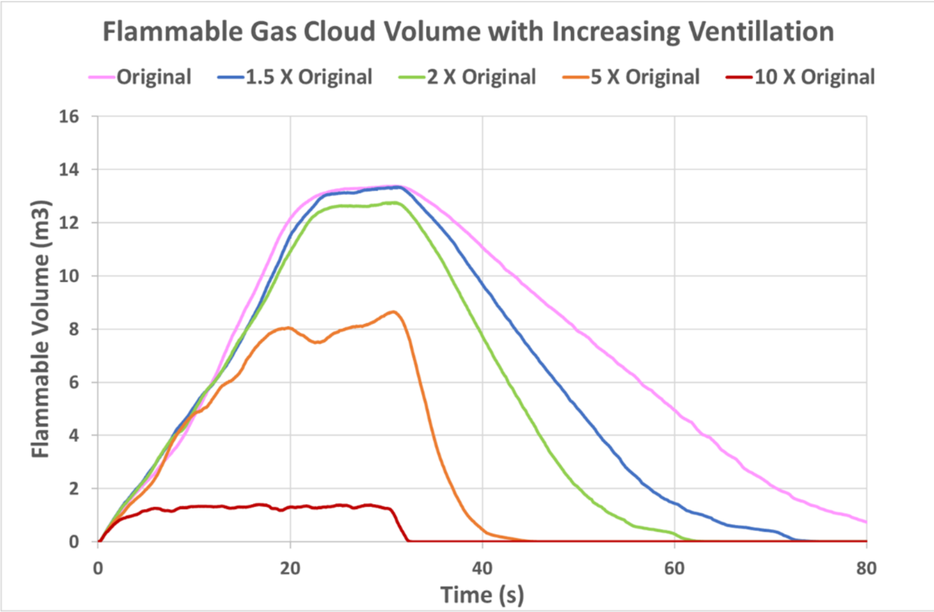


Figure 5. Volume of the flammable gas cloud for a 0.1 mm^2 leak lasting for 30 s for the ventilation rates studied.

It is clear that increasing the ventilation by a factor of 2 has a negligible effect on the maximum volume of the flammable cloud. The only improvement is that at higher ventilation rates the flammable cloud was diluted more quickly after the leak stopped. Only when the ventilation rate was increased by a factor of 5, a substantial decrease in the size of the flammable cloud was achieved, although an 8 m^3 hydrogen/air gas cloud is still likely to result in a powerful explosion. When the ventilation rate was increased to 10,000 m^3/h, the maximum size of the flammable cloud was decreased to 1.4 m^3.

Figure 6 shows the flammable cloud just before the leak was stopped (once it has reached its maximum size). The figure shows that, for the original ventilation rate of 1,000 m^3/h, the flammable cloud fills most of the enclosure. The fact that a significant part of the cloud was at a concentration where hydrogen displays high reactivity (between 20-30 vol%), means that in case of ignition the explosion overpressure could be very high (*vide infra)*. Increasing the ventilation rate by a factor of 5 visibly decreased the size of this high reactivity area, while a further increase to 10,000 m^3/h limited the high reactivity area to the immediate surrounding of the leak.

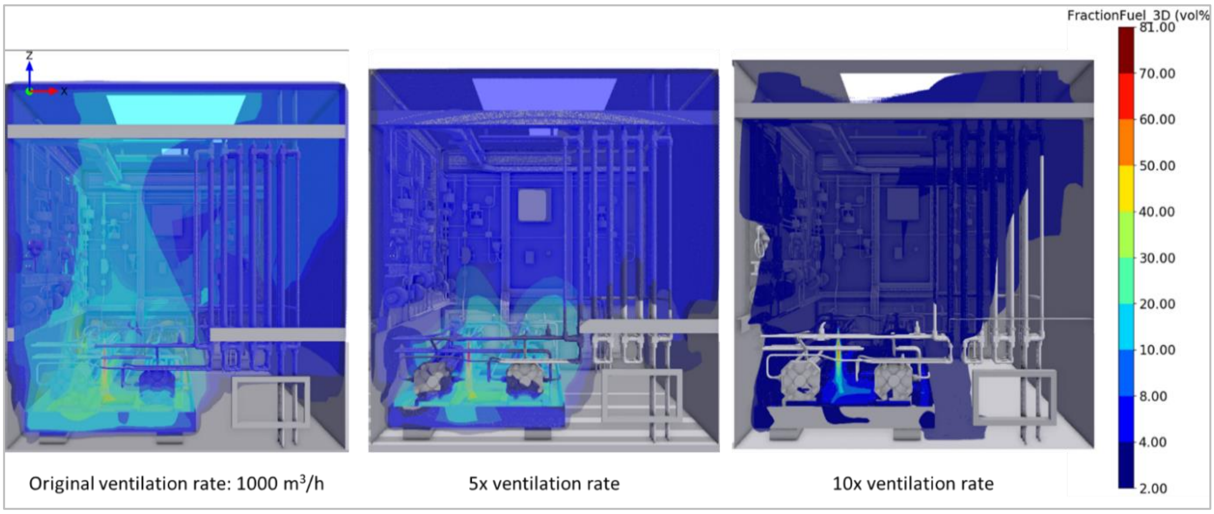


Figure 6. Maximum flammable gas cloud snapshot obtained for a 0.1 mm^2 leak lasting for 30 s for the different ventilation rates studied.

The gas clouds described above are inhomogeneous, meaning that some parts will be close to LFL (lean) and others close to the UFL (rich) and thus will have relatively low burning velocities. However, in such large flammable clouds, even small pockets where the gas/air mixture is close to the stoichiometric concentration (and thus corresponding to the maximum reactivity) can lead to high explosion overpressures likely to cause serious damage to the compressor enclosure and expose the public to fire, overpressure and flying debris hazards.

In order to investigate how the ventilation rate affected the cloud reactivity, the total volume of the flammable cloud was converted into an equivalent stoichiometric gas cloud using the Q8 concept. The Q8 cloud is the closed volume equivalent cloud at concentration for maximum expansion (normally near stoichiometry). This allows the scaling of the non-homogeneous gas cloud to a smaller stoichiometric gas cloud that is expected to give similar explosion loads as the original cloud. A similar concept but used for open environments (Q9) has been applied to hydrogen systems and has been found to give reasonably good predictions (Middha et al., 2006; Middha et al., 2008).

Figure 7 shows how the volume of the stoichiometric gas cloud (Q8) changes as the ventilation rate is increased. As before, only after the ventilation rate is increased 5-fold or more, an important decrease in the size of the Q8 cloud was observed. However, the increased ventilation has the effect of diluting the flammable cloud quicker after the leak is stopped. For the base-case ventilation rate of 1,000 m^3/h, it took almost a minute after the leak stopped for the flammable cloud to be diluted below LFL. In contrast, it took under 10 s to dilute the flammable cloud at 10,000 m^3/h. This has the effect of reducing the time during which the mixture is at risk of ignition.

The effect of the Q8 volume on the explosion overpressure is explored in the following section.

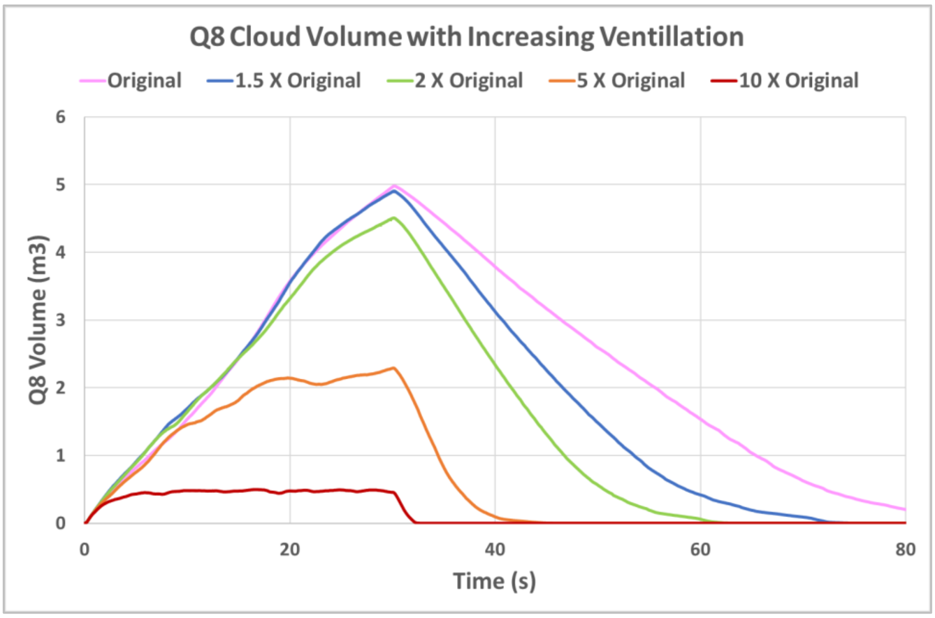


Figure 7. Volume of the stoichiometric gas cloud (Q8) for a 0.1 mm^2 leak lasting for 30 s for the ventilation rates studied.

Figure 8 shows the same analysis as before, but for a larger 0.5 mm^2 leak, lasting for 30 s. The figure shows that even the highest ventilation rate studied results only in a modest decrease in the size of the total flammable gas cloud. However, the size of the Q8 cloud decreases by almost 60% for the maximum ventilation rate compared with the base case of 1,000 m^3/h. Thus, the increased ventilation is having the effect of decreasing the overall reactivity of the cloud, even if the total volume of hydrogen between LFL and UFL is not changing drastically. Nevertheless, a 6 m^3 stoichiometric gas cloud is still likely to produce high overpressures that could damage the equipment and impact people in the vicinity.

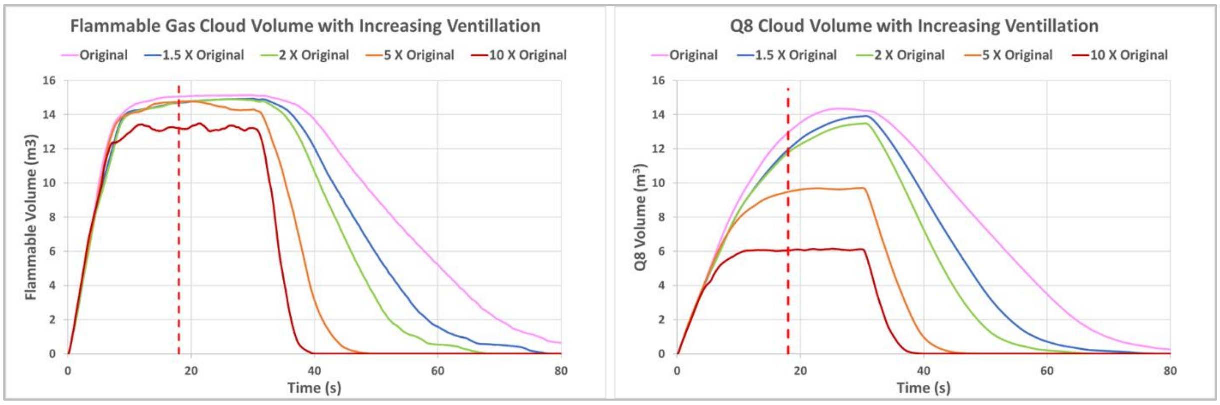


Figure 8. Volume of the flammable gas and stoichiometric gas cloud (Q8) for a 0.5 mm^2 leak lasting for 30 s for the ventilation rates studied.

Another interesting effect of the increased ventilation can be observed in Figure 8: about 18 s after the leak starts, the flammable gas cloud reaches its maximum size, even if the leak continues for a further 22s. For the smaller ventilation rates (up to 2,000 m^3/h), the Q8 cloud continues to increase, meaning that the leak continues to contribute towards the reactivity of the cloud. But for ventilation rates above 5,000 m^3/h, the size of the Q8 cloud stabilises for the duration of the leak and dissipates about 10 s after the leak is stopped. For the original ventilation rate, it takes over 50 s for the cloud to be diluted below LFL.

Explosion

The Q8 gas cloud was used for the explosion simulations. The ignition was located next to the leak, towards the bottom of the container. This conservative assumption would provide the longest flame path and for so the maximum flame acceleration. On the other hand, given that high-pressure hydrogen leaks can potentially auto-ignite, ignition can reasonably occur here.

The explosion simulations for the largest Q8 clouds resulted in very high overpressures (in the order of 7 bar), which could potentially trigger a deflagration-to-detonation transition (DDT). The detonation phenomenon is not modelled by FLACS-CFD, but overpressures in the order of 20-30 bar could be expected (Pekalski *et al*, 2015; Oran *et al.*; 2020). Nevertheless, even overpressures far below 7 bar would have potentially catastrophic consequences, with a high potential for escalation and harm to people.

Therefore, we decided to focus on the relative overpressure observed for the scenarios studied, to get an indication of the influence of the ventilation rate in mitigating the explosion overpressure. Figure 9 shows the overpressure ratio obtained for the simulations described above. Not surprisingly, only for ventilation rates above 5,000 m^3/h, a substantial decrease in explosion overpressure was observed, and only the highest ventilation rate studied resulted in an explosion overpressure that the container structure could be expected to withstand (comparing to values reported in IOGP 434-15) although no structural analysis has been performed.

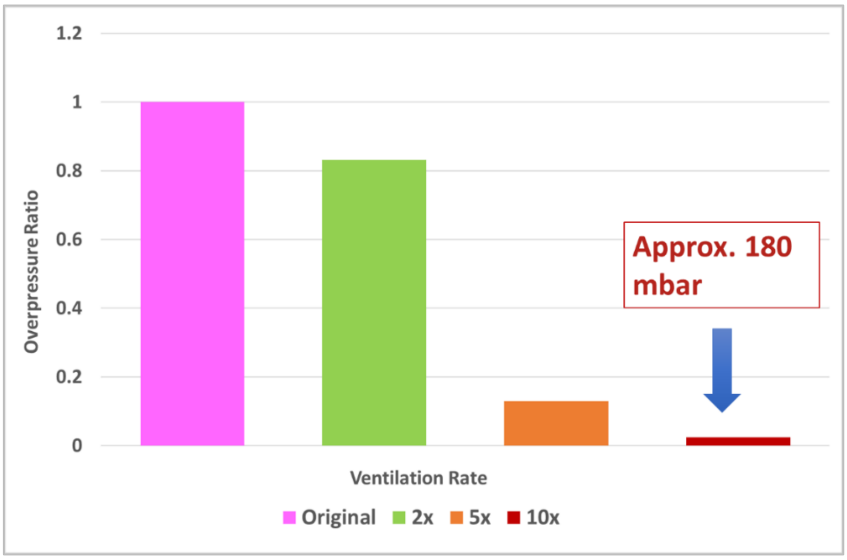


Figure 9. Variation of explosion overpressures with the ventilation rate. The overpressure calculated for the original ventilation rate was taken as 1.

In all cases the explosion relief panels opened, but this was insufficient to mitigate against the very high overpressures observed.

Conclusions

For very high-pressure applications, like those encountered in HRS, even a relatively small H_2 leak in an enclosed compartment cannot be effectively diluted with mechanical ventilation. Even for very high ventilation rates in the order of 10,000 m^3/h, potentially hazardous flammable gas clouds could be formed inside the container. Nevertheless, the higher ventilation rates (5x and 10x the base case) have the positive effect of reducing the reactivity of the gas cloud (shown here as the sizes of the Q8 cloud). Furthermore, with ventilation rates in the order of 10,000 m^3/h, the flammable cloud persisted only about 10 s after the leak is stopped, thus decreasing the time at risk for ignition.

This study demonstrates that the configuration of the ventilation system needs to be optimised, as in the current configuration (inlet openings at the bottom and extraction fan at the top) high air speeds were only achieved close to the inlet/ outlet points. A ventilation system including local extraction close to the points where leaks are expected (additional to background ventilation) would likely improve the overall airflow condition and thus reduce the accumulation of flammable gases in the enclosure.

Aside from ventilation, other mitigation measures should be considered to decrease the risk of a severe explosion. Rapid detection and shut-down are essential to control the size and reactivity of the flammable cloud. Even when the gas cloud fills the enclosure, reducing the leak duration limits the reactivity of the cloud, thus limiting the potential explosion overpressures in case of ignition. For high-pressure systems, differential pressure measurement might provide a quicker detection method than flammable gas detectors.

To avoid catastrophic failure and potential for escalation from over-pressure and flying debris, the use of explosion relief panels should be considered. However, it is necessary to ensure that these provide enough venting surface and open early enough in the explosion process to be able to break the explosion feedback loop which leads to high overpressures. Explosion modelling studies with different relief panels configurations (location, venting area, opening pressure) could be carried out to inform the design of the venting arrangement.

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