Modelling studies of the hazards posed by liquid hydrogen use in civil aviation

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Abstract. As part of the ENABLEH2 project, modelling studies have been carried out to examine liquid hydrogen release and dispersion behaviour for different LH2 aircraft and airport infrastructure leak/spill accident scenarios. The FLACS CFD model has been used to simulate the potential hazard effects following an accidental LH2 leak, including the extent of the flammable LH2 clouds formed, magnitude of explosion overpressures and pool fire radiation hazards. A comparison has also been made between the relative hazard consequences of using LH2 with conventional Jet A/A-1 fuel. The results indicate that in the event of accidental fuel leak/spill LH2 has some safety advantages over Jet A/A-1 but will also introduce additional hazards not found with Jet A/A-1 that will need to be carefully managed and mitigated against.

1. Introduction

The use of liquid hydrogen (LH2) as a fuel can potentially enable civil aviation to deliver zero CO_2 and NOx emissions and offer a long-term sustainable solution. The usage of LH2 as an aviation fuel will require the development of new types of aircraft and cryogenic fuel tank design, as well as the need for large-scale LH2 aircraft refuelling operation and storage facilities at airports. A key challenge that will need to be met in order to allow such a transition is that of safety. Hydrogen has unique properties and behaves very differently to conventional aircraft fuel. However, only a limited amount of information is currently available examining the behaviour and the extent of flammable gas clouds, pool fires and explosions resulting from LH2 spills, particularly in the context of the aircraft and airport safety. As part of the ENABLEH2 (ENABLing cryogEnic Hydrogen based CO_2 free air transport) project [1], modelling studies have therefore been carried out (primarily using the FLACS-CFD code), to examine and predict the behaviour of accidental LH2 releases in terms of the hazards and safety challenges they could present and how these compare with the existing hazards posed by using conventional aviation fuel (Jet A). An overview of some of the key results found in the work is presented here (for further details see [1]).

1.1. Hazard types and accident scenarios

The main aim of this work has been to study the large-scale hazards posed by LH2 use in civil aviation carry out LH2 release and dispersion modelling of large-scale releases and their potential hazard effects for airport storage and aircraft tank failure/rupture/leak scenarios. A variety of different hazard types and accident scenario case studies have been considered. These include:

- LH2 spills during aircraft refuelling operations
- Aircraft LH2 fuel tank leak/rupture
- Airport LH2 storage tank leak/rupture

Following a LH2 release due to an accidental leak or rupture (initiating event) a range of different hazards and consequent effects can occur depending upon the nature of the release and as to whether or when an ignition source is introduced [2]:

- *Immediate ignition – Fire*: In the event of an immediate ignition of the LH2 release the hydrogen will burn as a fire, emitting thermal radiation and causing harm via burn injuries/fatalities, structural damage and incident escalation.

- *Delayed ignition - Flash Fire\Explosion*: In this case the hydrogen gas release will disperse and travel away from the spill point forming a flammable gas cloud. If it should then encounter a remote ignition source then the cloud could ignite resulting in a flash fire causing burn injuries/fatalities or (if in a congested or confined area) a vapour cloud explosion causing harm via blast injuries/fatalities, structural damage and incident escalation. The flame can also propagate back to the LH2 pool producing a pool fire.

For LH2 stored in a tank the initiating LH2 release event can also take the form of a catastrophic rupture, resulting in a boiling liquid expanding vapour explosion (BLEVE). Such an explosion can occur for liquids, such as LH2 when, they are stored at temperatures above their boiling point at atmospheric pressure, resulting in a rapid expansion of the contents if the vessel should fail. Tank BLEVEs can be triggered via heating of the tank by an external fire, a violent impact, failure of pressure relief valve, or a fault in the vessel insulation. The hazardous consequences of a tank BLEVE are manifested through the generation of a pressure wave, the production of missiles and fragments as the vessel is torn apart and if ignited, a fireball [2].

1.2. The FLACS CFD Model

In the study numerical simulations were performed using the FLACS CFD model [3]. FLACS was originally developed in the 1980 and 90s for use in the Oil and Gas industry. It provides capabilities for carrying out safety studies by simulating accident scenarios involving fluid flow behaviour in complex 3D geometries by modelling flammable gas hazard effects such as: dispersion of flammable gases; gas explosions and blast waves and pool; and jet fires

FLACS is a structured Cartesian grid, finite volume CFD code. The code solves the compressible conservation equations for mass, momentum, enthalpy, mass fraction of chemical species, turbulent kinetic energy and dissipation rate of turbulent kinetic energy. The numerical treatment used in FLACS solver employs a second order scheme in space, and a first/second order in time. A standard k-ε turbulence model is also utilised incorporating modifications for generation of turbulence behind sub-grid obstacles and turbulent wall functions. FLACS employs the Porosity/Distributed Resistance method to model the turbulence generated by subgrid scale objects. This allows for the efficient simulation of gas dispersion behaviour in complex geometries using relatively coarse numerical grids. Further technical details of the FLACS CFD model can be found in [3].

1.3. FLACS simulations

In the case of LH2 pool fire spills, the hydrogen gas release generated by each spill volume considered was represented as an area leak in FLACS. The variation in the size (area) and mass vaporisation rate of this leak versus time was defined via a FLACS input leak file based upon the results predicted by the FLACS pool model for the vaporisation of that LH2 spill volume. In the case of instantaneous release of Jet A/A-1 the area of the pool formed for a given spill volume was calculated by assuming the pool will instantaneously spread to the minimum pool thickness - equal to the characteristic surface roughness [4]. A value of 5 mm was used, which is representative of a relatively smooth surface like concrete [5]. The FLACS fuel type "Dodecane" was used to represent Jet A/A-1, and a constant fuel mass vaporisation rate per unit area of 0.063 kg/m^2/s was assumed (based upon test data for kerosene [6].

In the case of LH2 spills which are not ignited immediately a flammable hydrogen gas cloud will be formed, the development of which can be simulated using the FLACS dispersion model. The hazard presented by a flash fire resulting from a delayed ignition of this cloud was characterised in terms of the region of the hydrogen cloud found in the dispersion simulations that was above the LFL of hydrogen (assumed to be 4% v/v although this may be different at cryogenic temperatures) or the maximum downwind distance from the spill origin to the LFL boundary of the simulated cloud. An examination of the explosion hazard presented by different spill cases was also carried out by introducing an ignition source to the flammable cloud obtained in the dispersion simulations after a particular time interval, and then simulating the resulting flame propagation and overpressure development behaviour.

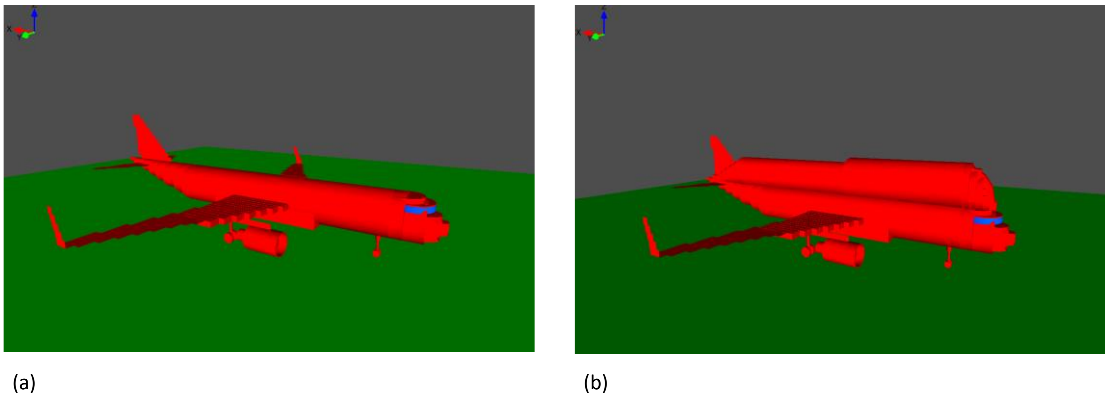

(a) (b)

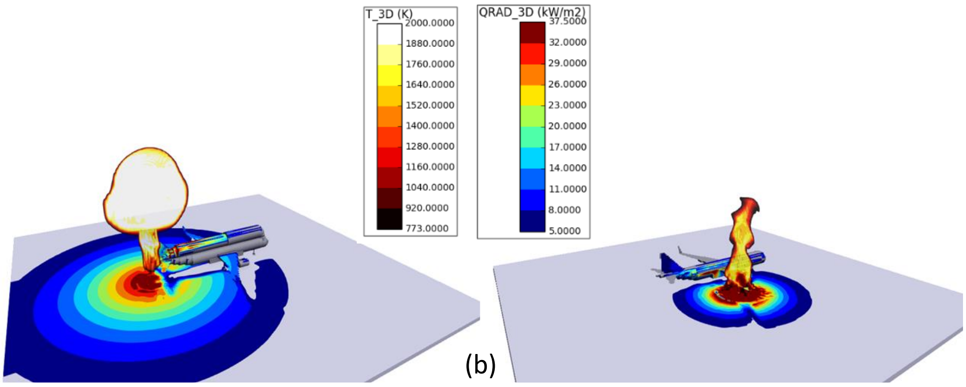
Figure 1 - The aircraft geometries introduced into FLACS: (a) conventional Jet A aircraft; (b) LH2 short/medium range "tube and wing" aircraft.

In order to examine the effect of aircraft geometry upon hazard behaviour both a conventional commercial short/medium range passenger aircraft design and a modified short/medium range 'tube and wing' LH2 aircraft design developed for ENABLEH2, were digitised, and introduced as geometrical objects (comprised of boxes, cylinders and plates) into FLACS. Figure 1(a) shows the conventional aircraft geometry used, whilst Figure 1(b) shows the LH2 aircraft geometry (with the LH2 tanks located in the fairing above the main body of the aircraft).

2. Pool fire simulation results (LH2 vs Jet A)

Work has been carried out to examine the consequences of an instantaneous fuel spill and immediate ignition event resulting in a pool fire occurring during aircraft refuelling operations, comparing the behaviour of LH2 and Jet A whilst also including the aircraft geometry as part of the simulation.

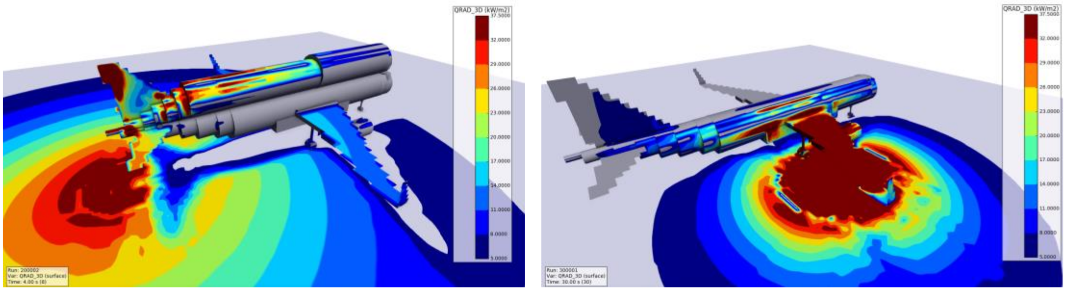
FLACS simulations were performed to allow a comparison to be made between the pool fires resulting from a 500 L instantaneous spill of LH2 and Jet A (kerosene). The Jet A spill/pool fire was located under the wing (corresponding to the location of the refuelling point used for a conventional Jet A aircraft). The LH2 spill/pool fire was assumed to be located in one of two positions – either on the right side of the aircraft fuselage towards the front of the aircraft ahead of the wing, or at the tail of the aircraft. The simulations carried out were used to compare pool fire behaviour, radiation heat flux and thermal radiation dose exhibited by the two fuels.



(b)

Figure 2 – (a) The fireball formed in the 500 L instantaneous spill LH2 pool fire located at the tail of the aircraft; (b) The fire plume formed in the 500 L Jet A spill pool fire located under the aircraft wing.

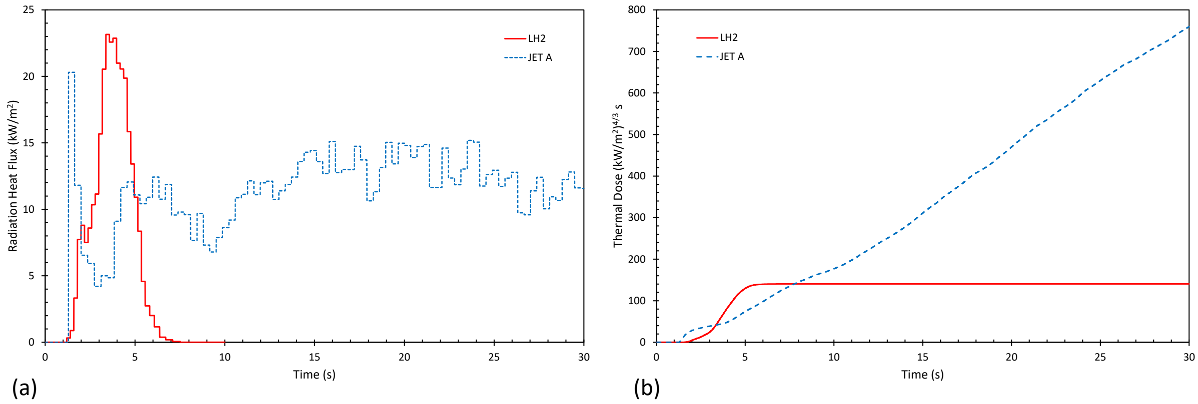
Figure 2(a) illustrates the fireball formed during the 500 L instantaneous spill LH2 pool fire located at the tail of the aircraft. The LH2 spill vaporises rapidly and the ignited hydrogen gas forms a fireball - a rapidly rising expanding ball of flame. The resulting high intensity fire has a relatively high heat release rate over a short period of time before consuming the available fuel and burning out. The corresponding thermal radiation flux incident on the ground and aircraft surfaces is also shown. In this case the radiation heat flux released by the rising fireball falls mainly to the rear of the aircraft, with the highest intensities produced on the tail and top of the fuselage. The fire plume formed during the 500 L Jet A spill pool fire is shown in figure 2(b). In comparison to the intense fireball produced for LH2, the Jet A pool fire has a flame that burns continuously with a lower peak HRR, but that which is sustained over a significantly longer period of time. Figure 3(a) shows a closer view of the radiation heat flux incident of the aircraft from the LH2 pool fire after 4 s. In this case the radiation heat flux released by the rising fireball falls mainly to the rear of the aircraft, with the highest intensities produced on the tail and top of the fuselage. Figure 3(b) shows the radiation heat flux from the Jet A pool fire which is concentrated along the length of the right side and wing of the aircraft. The size and duration of the very high thermal flux region (> 37.5 kW//m^2) produced by the Jet A fire (e.g. on the right wing and engine) is also predicted to be significantly greater than that for the LH2 fire. However, the results also suggest that the fuselage of the aircraft does effectively shield the left-hand side of the aircraft from the radiation produced by the Jet A fire.



(a) (b)

Figure 3 – Comparison of the radiation heat flux incident on the aircraft: (a) LH2 pool fire after 4s; (b) Jet A pool fire after 30 s.

A comparison of radiation heat flux received at a monitor point located on the ground 15 m from the centre of the pool fire (selected as a suitable reference scale corresponding to the distance between the fuselage and wing tip) is given in figure 4(a). This shows a short duration curve (around 6s) with a sharp peak flux (over 20 kW/m^2) produced for the LH2 pool fire compared to the radiation flux fluctuating at a lower level (between 10 to 15 kW/m^2) over a longer period for the Jet A pool fire. The level of harm inflicted by the thermal radiation released from a fire depends both upon the intensity of the thermal radiation flux received by the target and the duration of exposure. This harm level is usually expressed in terms of the thermal radiation dose. Figure 4(b) shows a comparison of the thermal dose received at a monitor point located on the ground 15 m from the centre of the 500 L LH2 and Jet A pool fires. As a consequence of the short duration of the LH2 fireball the total thermal dose delivered levels off (at around 150 (kW/m^2)$^{4/3}$ s) after 6 seconds whilst the dose delivered from the Jet A pool fire continues to increase to reach a total around 5 times that of the LH2 pool fire after 30 s. Hence a significantly lower total thermal radiation dose is delivered by the LH2 pool fire.



(a) (b)

Figure 4 - Comparison of the (a) predicted radiation heat flux and (b) thermal radiation does produced by the LH2 and Jet A 500 L fuel spill pool fires received at a monitor point 15 m from the origin of the fire.

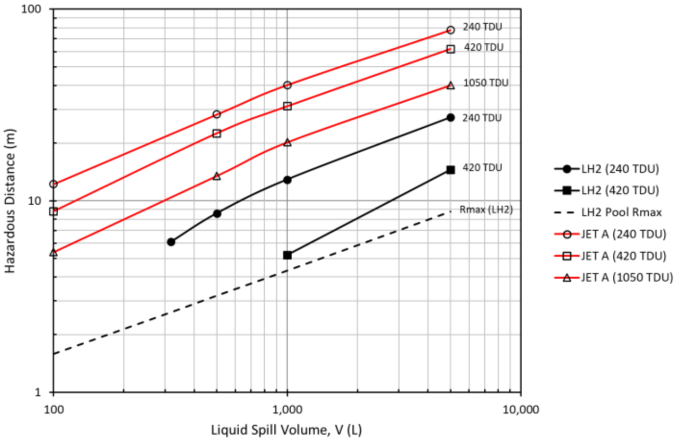


Figure 5 - Comparison of hazardous distance vs. spill volume predicted for LH2 and Jet A fuel spill pool fires, at different thermal dose thresholds.

By comparing the predicted thermal radiation dose produced at different distances from a pool fire with specified dose harm criteria [7] the hazardous distance from the fire origin producing a given harm threshold can be determined for both LH2 and Jet A spills. Figure 5 compares the hazardous distance predicted by FLACS-Fire for the different thermal radiation dose harm thresholds as a function of the liquid spill volume for both LH2 and Jet A pool fires. It is evident that, as a consequence of the short duration of the LH2 fireball, the hazardous distance predicted for the LH2 pool fires are significantly lower than those obtained for an equivalent spill volume of Jet A. In fact, not only is the hazardous distance to the 240 TDU (2nd degree burn) injury threshold predicted for LH2 pool fires (for a given spill volume) to be much less than that found for Jet A (around a third the value), but it is also less than the distances to the 420 TDU (dangerous dose) and 1050 TDU (fatality) thresholds predicted for Jet A. In the case of the instantaneous LH2 pool fires simulated, the 1050 TDU thermal dose threshold for a fatality was not exceeded. To provide a lower bound on the hazardous distance for these cases the maximum radius of the LH2 spill/pool fire region has therefore also been plotted in figure 5.

3. Dispersion and explosion simulation results (LH2)

LH2 spills can also exhibit additional modes of hazardous behaviour (not found for Jet A under typical operating conditions) through the formation and dispersion of flammable gas clouds and associated flame propagation and explosion behaviour. Work has also therefore been carried out to model the consequences of accidental LH2 spills, in the case of delayed ignition of the resulting hydrogen gas cloud. Previous work focused on modelling the dispersion behaviour of the flammable gas cloud produced by LH2 leaks [8]. The work described here has been extended to examine the effect of aircraft geometry upon hazard behaviour. Depending upon the hydrogen concentration and the levels of confinement/ congestion the delayed ignition of the flammable gas cloud could result in either a flash fire or explosion. The FLACS CFD model was used to simulate the flammable hydrogen clouds produced for a short duration LH2 leak from an aircraft during refuelling. The effect of different leak locations, wind directions and leak duration upon the resulting flammable cloud were examined.

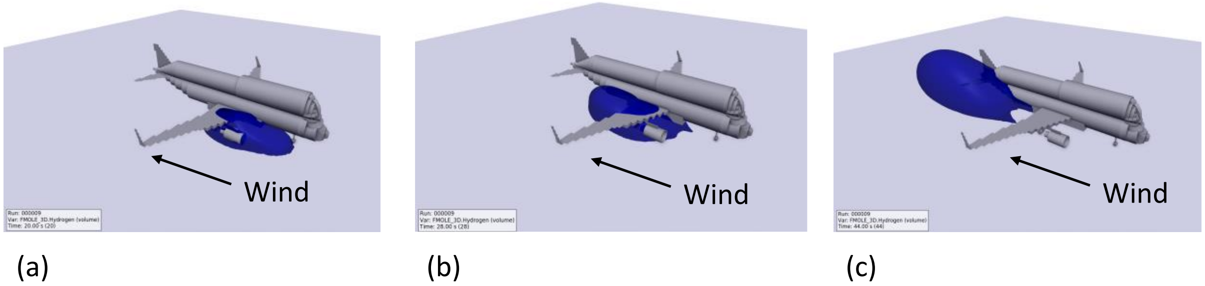


Figure 6 - Dispersion of the hydrogen cloud (4% LFL iso-surface) formed following a 5 s LH2 fuel spill with a wind 2 m/s running nose to tail (Case A) after: (a) 20 s; (b) 28 s; (c) 44 s.

Figure 6 shows an example of the flammable cloud dispersion behaviour (4% LFL iso-surface) of a short duration 5s spill of LH2 from a location on the right side of the aircraft parallel to the front wheel, with a wind of 2 m/s running nose to tail. The dense cryogenic hydrogen released by the vaporising LH2 pool forms a discrete flammable cloud which is transported by the wind along the right side of the aircraft, moving around the wing and past the end of the tail before dispersing below the LFL.

In some simulations a delayed ignition source was also introduced to allow the explosion overpressure resulting from ignition of the flammable clouds produced for different scenarios to be predicted. The results suggest that the magnitude of the overpressure produced is typically relatively low, extending over only a small region in the vicinity of the leak. However, there were also a few scenarios, involving ignition of clouds formed under the body of the aircraft, where the results indicated the potential for flame acceleration to occur, which could lead to much higher overpressures occurring over a wider area.

4. Comparison of hazardous distance for different aircraft/airport accident scenarios

Table 1 presents a comparison of the hazardous distances predicted for different aircraft and airport accident scenarios involving releases of LH2 or Jet A. Given the limited validation and associated level of uncertainty over the predicted results the aim of the analysis here is to observe general trends and make relative comparisons between the LH2 hazards resulting from different accident scenarios and the behaviour of LH2 versus Jet A. It is evident from the results that the hazardous distance due to thermal radiation dose from a pool fire is predicted to be significantly less for LH2 than is the case for Jet A. This is primarily due to the much shorter vaporization and burning time of the LH2 pool fire, along with the lower radiation fraction. However, LH2 spills also present additional safety hazards not exhibited by Jet A in the form of the flammable gas cloud formed and the potential for a flash fire, jet fire, explosion or BLEVE to occur.

Table 1 - A comparison of the hazardous distances estimated for different aircraft and airport accident release scenarios involving LH2 or Jet A.

Case	**Initiating event**	**Spill/leak scenario**	**Ignition type**	**Hazard type**	**Harm criteria**	**Hazardous distance (m)**	
						LH2	**Jet A**
IC-1	Aircraft refuelling spill 50 mm hose rupture	4.5 kg/s for 5 s pool	Delayed	Flammable cloud	4% LFL	73 m	n/a
			Delayed	Explosion o/p	0.07 barg	20 m	n/a
IP-1		100 L pool	Immediate	Pool fire	240 TDU	2 m	12 m
IP-2		500 L pool	Immediate	Pool fire	240 TDU	9 m	27 m
IP-3		1000 L pool	Immediate	Pool fire	240 TDU	13 m	44 m
IP-4		5000 L pool	Immediate	Pool fire	240 TDU	27 m	78 m
IP-5		4.5 kg/s for 5 s pool	Immediate	Pool fire	240 TDU	6 m	22 m
JP-1		50 mm hose: jet	Delayed	Jet plume	4% LFL	67 m	n/a
JF-1		50 mm hose: jet	Immediate	Jet fire	$5\ \text{kW/m}^2$	30 m	n/a
JP-5	Venting aircraft tank 25 mm vent line	25 mm hole: jet	Delayed	Jet plume	4% LFL	30 m	n/a
JF-5		25 mm hole: jet	Immediate	Jet fire	$5\ \text{kW/m}^2$	6 m	n/a
CP-1	Severed engine fuel line	0.6 kg/s LH2 pool[a] 9.0 kg/s Jet A pool[a]	Immediate	Pool fire	240 TDU	7 m	33 m
JP-0		25 mm hole: jet	Delayed	Jet plume	4% LFL	35 m	n/a
JF-0		25 mm hole: jet	Immediate	Jet fire	$5\ \text{kW/m}^2$	20 m	n/a
CP-3	Aircraft fuel tank leak	100 mm hole: pool	Immediate	Pool fire	240 TDU	34 m	43 m
CC-3		100 mm hole: pool	Delayed	Flammable cloud	4% LFL	244 m	n/a
JP-3		100 mm hole: jet	Delayed	Jet plume	4% LFL	100 m	n/a
JF-3		100 mm hole: jet	Immediate	Jet fire	$5\ \text{kW/m}^2$	55 m	n/a
CP-4	Storage tank leak	100 mm hole: pool	Immediate	Pool fire	240 TDU	40 m	70 m
CC-4		100 mm hole: pool	Delayed	Flammable cloud	4% LFL	333 m	n/a
JP-4		100 mm hole: jet	Delayed	Jet plume	4% LFL	100 m	n/a
JF-4		100 mm hole: jet	Immediate	Jet fire	$5\ \text{kW/m}^2$	75 m	n/a
BV-1	Aircraft tank BLEVE	5 t (Entire fuel load)	Immediate	Fireball	240 TDU	236 m	n/a
BV-2	Storage tank BLEVE	250 t	Immediate	Fireball	240 TDU	1208 m	n/a

[a] The fuel leak rates examined were based upon the LH2 and Jet A severed fuel line accident scenarios described in [9].

The largest predicted hazardous distances are associated with LH2 tank BLEVE accident scenarios – particularly the airport storage tank BLEVE, which is predicted to have a hazardous distance of around 1.2 km. However, tank BLEVEs would be expected to be highly unlikely events. Given the extremely hazardous consequences predicted for such events, in-depth safety measures (e.g. pressure relief devices, multiple redundant vents etc.) will be required to ensure that this is indeed the case. The accident scenarios involving very serious continuous leaks of LH2, from 100 mm holes in aircraft fuel tanks or airport storage tanks, are also estimated to be capable of producing flammable gas clouds with very large hazardous distances of up to several hundred metres. Such serious leaks would also be expected to be highly unlikely events. However, if the risk is judged to be sufficiently high, measures may still be required to mitigate against their consequences.

5. Conclusion

Modelling studies have been carried out to examine liquid hydrogen release and dispersion behaviour for different LH2 aircraft and airport infrastructure leak/spill accident scenarios. The results of the study indicate that, in the event of accidental fuel spill, LH2 may have some safety advantages over Jet A/A-1. Modelling of LH2 pool fires suggests they will exhibit a smaller thermal radiation hazardous distance and deliver a lower thermal dose than those found for a comparable Jet A/A-1 pool fire. The rapid vaporisation of instantaneous LH2 spills produces short duration fires such that the fuel spills will completely evaporate and burn-out rapidly. Hydrogen fires are also expected to emit a lower fraction of their heat as radiation and be clean burning such that no toxic smoke is produced (unless other materials become involved). However, the use of LH2 fuel will also introduce additional hazards not found with Jet A/A-1 that will need to be carefully managed and mitigated against. The largest hazardous distances are predicted to occur for LH2 tank BLEVE accident scenarios – particularly airport storage tank BLEVEs. There are also additional hazards associated with LH2 leaks and spills due to dense gas cloud dispersion behaviour that is predicted and the extent of flammable gas cloud that can be formed at ground level downwind of the spill and potential for accompanying flash fire/jet fire and explosion hazards. The hazard consequences produced may be accentuated if the prevailing wind could transport the cloud under the body of the aircraft where it could be partially confined, towards the airport terminal building, or to the side of the aircraft where passengers' egress.

It should also be noted that there is significant uncertainty associated with the predictions of current hazard models when applied to LH2 behaviour and the limitations should be borne in mind when interpreting or making judgements based on the results. There is also an urgent requirement for more large-scale experimental test data for LH2 releases and associated hazard behaviour in order to reduce uncertainty and allow models to be further developed and validated to improve confidence in their predictions.

Acknowledgments

This work was carried out for the ENABLEH2 project funded by the European Union H2020 programme under GA no. 769241.

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2022-02-15

Holborn PG, Ingram JM, Benson CB. (2022) Modelling studies of the hazards posed by liquid hydrogen use in civil aviation, IOP Conference Series: Materials Science and Engineering, Volume 1226, 2022, Article number 012059

https://doi.org/10.1088/1757-899X/1226/1/012059