



Throughout multiphase CFD model of BLEVE phenomena: from blast wave to fireball

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ELVHYS Dissemination Conference
16-17 September 2026, Brussels, Belgium



ELVHYS project No. 101101381 is supported by the Clean Hydrogen Partnership and its members. UK participants in Horizon Europe Project ELVHYS are supported by UKRI grant numbers 10063519 (University of Ulster) and 10070592 (Health and Safety Executive)

Introduction

- Liquid hydrogen (LH_2) storage tanks are equipped with pressure relief devices (PRD) to vent hydrogen and avoid the pressure build-up.
- In case of tank structural integrity or PRD failure in conditions of fire, a storage tank can catastrophically rupture.
- The tank rupture results in what is called a boiling liquid expanding vapour explosion (BLEVE) with consequent:
 - Blast wave;
 - Fireball;
 - Projectiles.



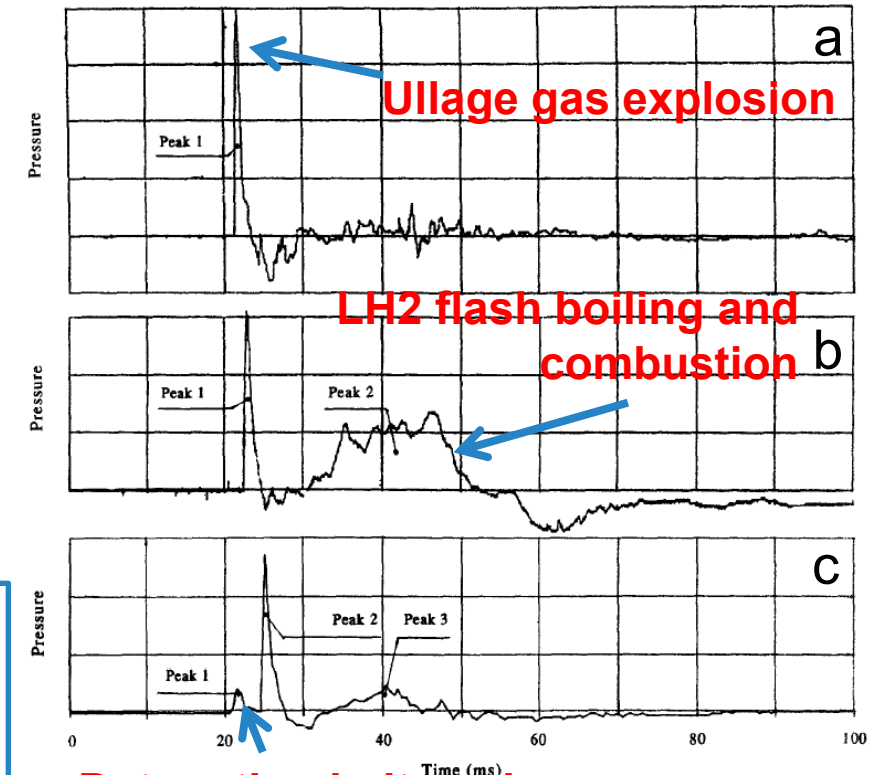
Catastrophic rupture of a 76 m³ LH_2 storage tank (Shen and Miller, 2024).

Knowledge gaps on understanding of LH₂ BLEVE

- The underlying physical mechanisms leading to the generation of blast waves after LH₂ storage tank rupture are not yet fully understood.
- Authors' study on "rethinking BLEVE" concluded that:
 - The maximum blast wave pressure is generated by the GH₂ phase starting shock.
 - BLEVE pressure peak follows the GH₂ phase blast.
- Absence of numerical models capable to reproduce blast wave and fireball from LH₂ BLEVEs accounting for both multiphase and combustion modelling.

Aim of the research:

Develop a novel "throughout" model able to simulate the multi-peak blast wave structure and the entire fireball dynamics of a LH₂ storage tank BLEVE, as observed experimentally by (Pehr, 1996).



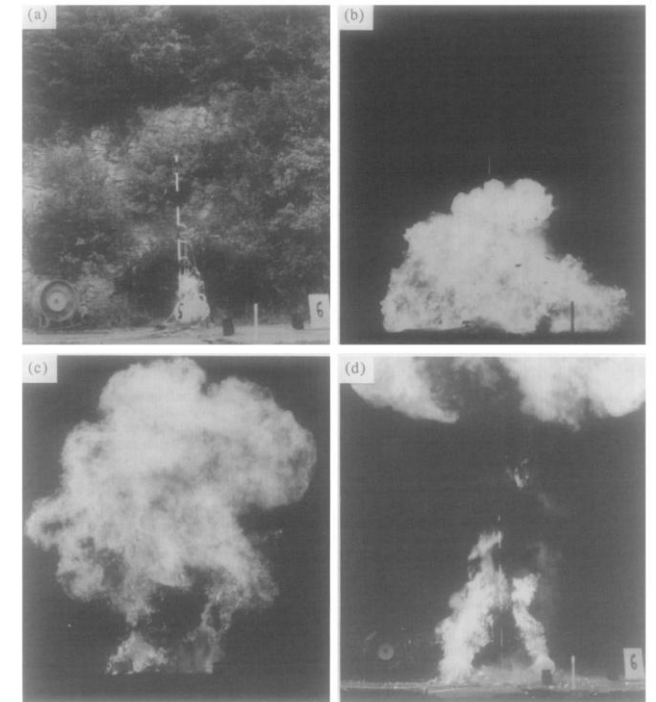
Detonation belt peak

Typical pressure transients at 3 m from the tank centre with one (a), two (b) and three (c) distinctive peaks in BMW experiments (Pehr, 1996).

Real scale “BMW” tests on BLEVE

- BMW experiments on the “controlled” rupture of LH₂ storage tanks by an explosive charge.
- Cylindrical storage tank with volume 0.12 m³.
- Stored H₂ mass: 1.8-5.4 kg (unknown mass for each test).
- Tank storage pressure: 0.2-1.5 MPa(a).
- Blast overpressure was measured at 3 m from the tank (availability of only maximum overpressure).
- Maximum fireball diameter: 20 m.

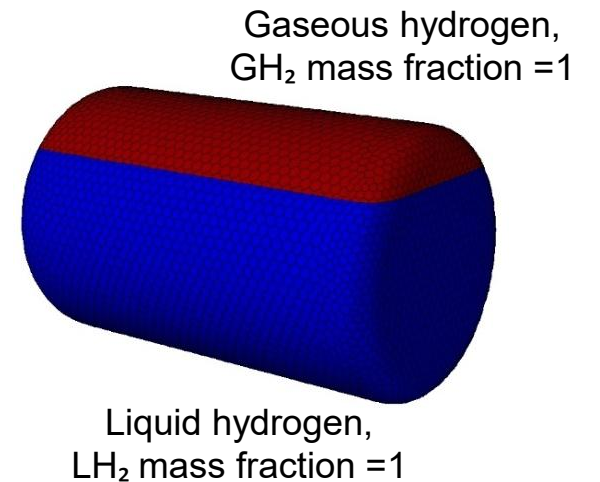
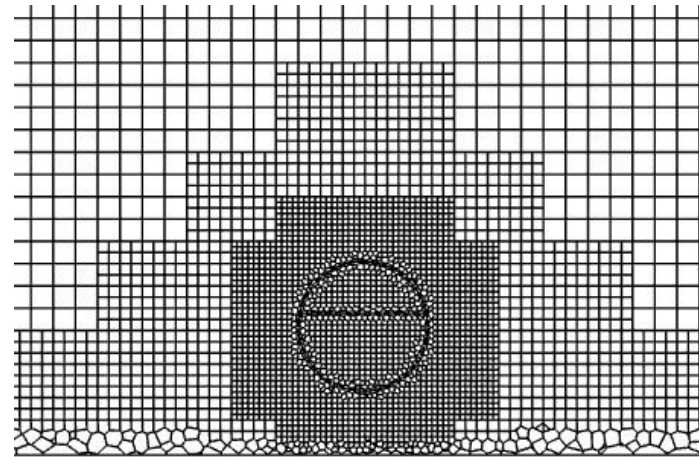
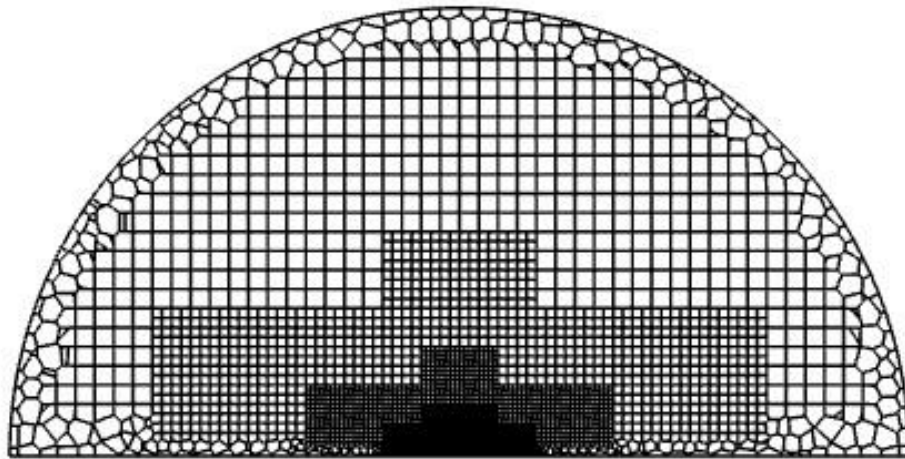
Test No.	1	2	3	4	5	6	7	8
Tank storage pressure, MPa(a)	0.2	0.21	0.37	0.4	0.4	1.1	1.1	1.13
Blast overpressure at 3 m, kPa(g)	16.7	3.3	6.0	7.7	11.0	13.3	47.0	15.0



Development of a fireball: a) Ignition ($t=0$), b) $t=250$ ms, c) $t=1250$ ms, d) $t=1800$ ms (Pehr, 1996).

CFD model and numerical details

- Large Eddy Simulations (LES) approach with Volume of Fluid for multiphase modelling.
- Combined Finite Rate and Eddy Dissipation Model for combustion.
- The numerical domain is a poly-hexa hemispherical grid (400-700k CVs) with radius up to 120 m.
- Numerical simulations for each test pressure were performed for the minimum and maximum possible total H_2 masses within the experimental range 1.8-5.4 kg.



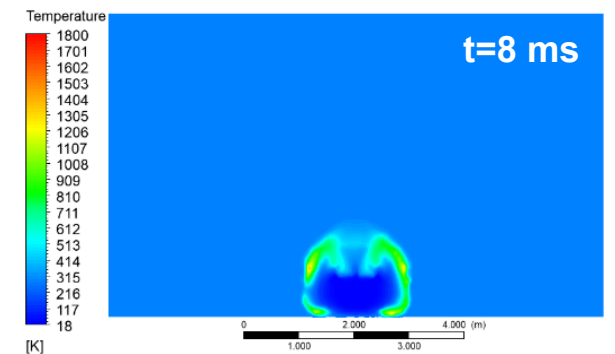
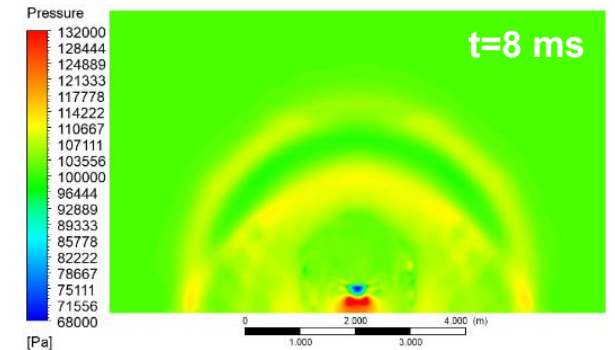
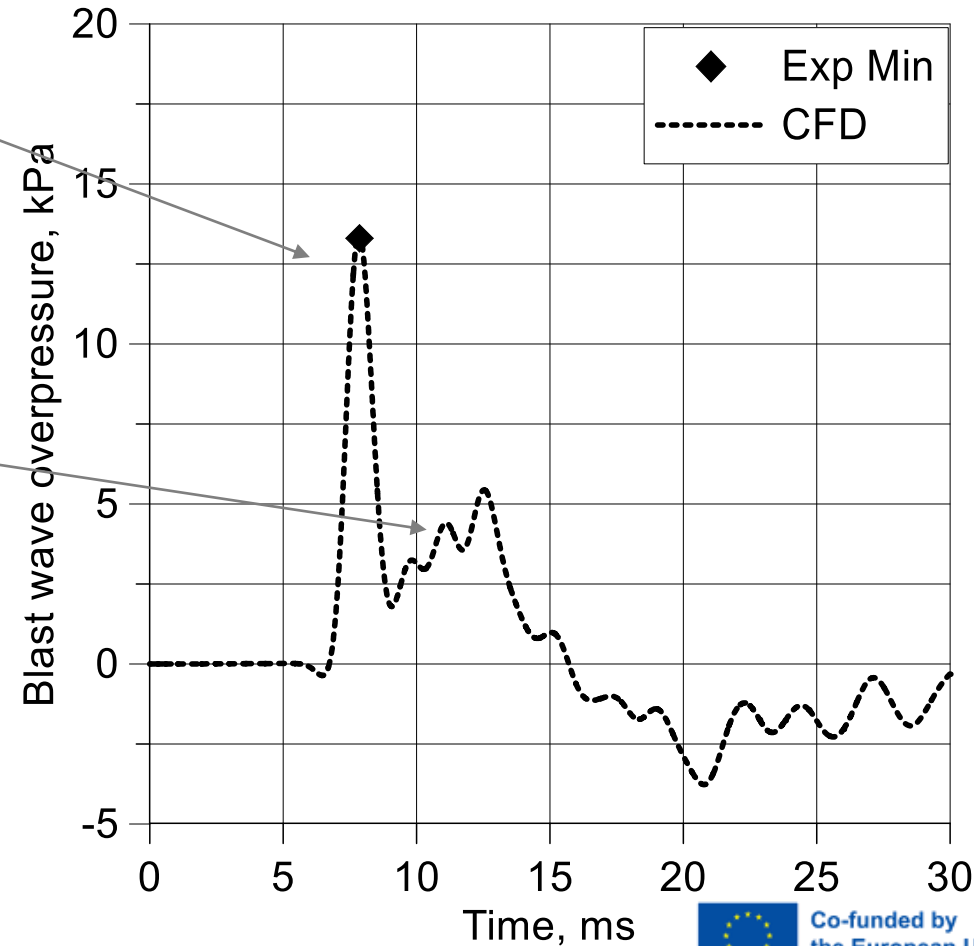
Simulations of multi-peak overpressure dynamics

$P_s=1.1$ MPa(a) and H_2 mass=5.4 kg

Simulated overpressure at 3 m perpendicularly to the storage tank.

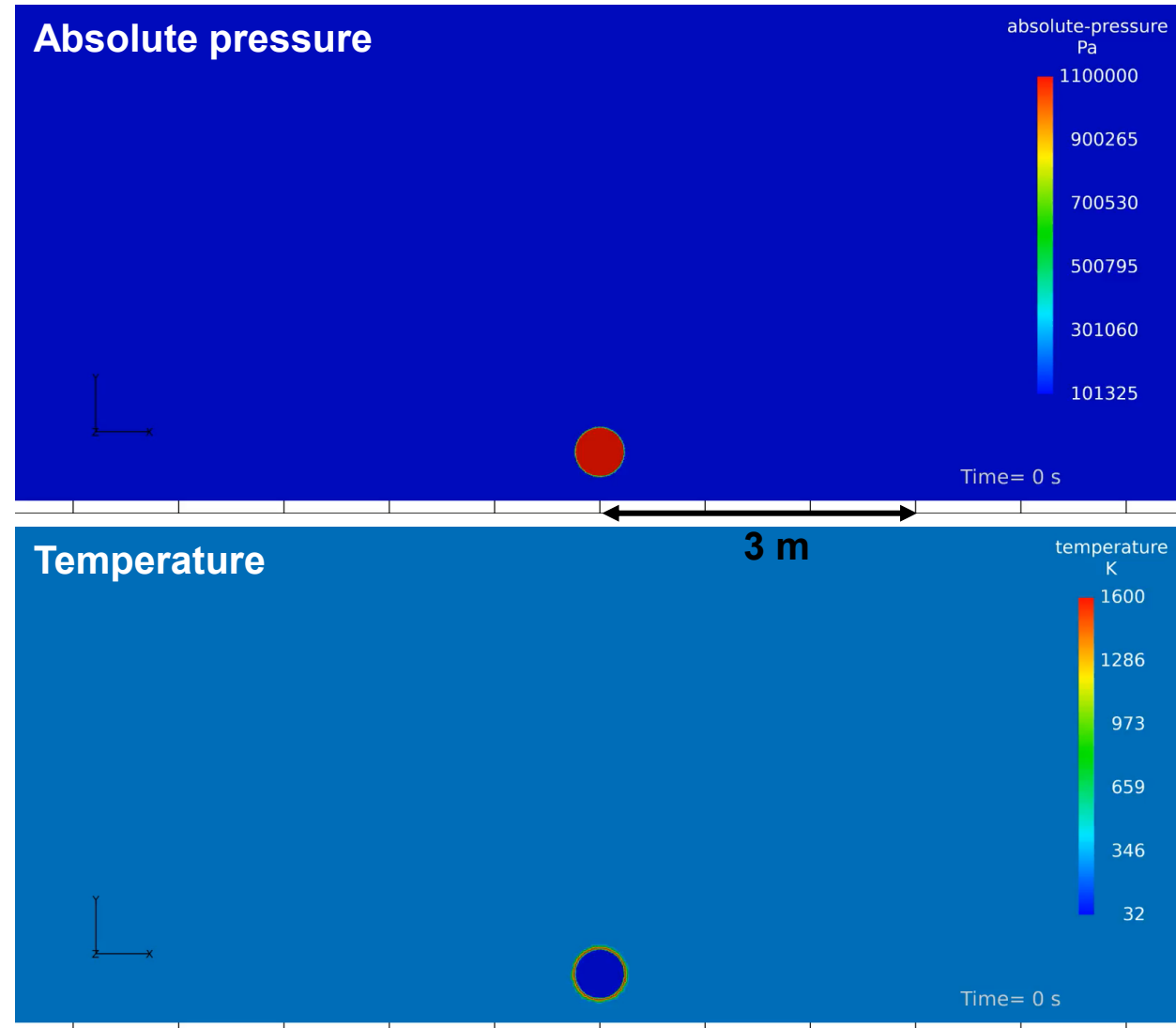
Peak 1:
CGH₂ phase shock with
contribution of combustion

Peak 2:
LH₂ flash boiling and
expansion



Pressure and temperature dynamics

$P_s=1.1$ MPa(a) and H_2 mass=5.4 kg

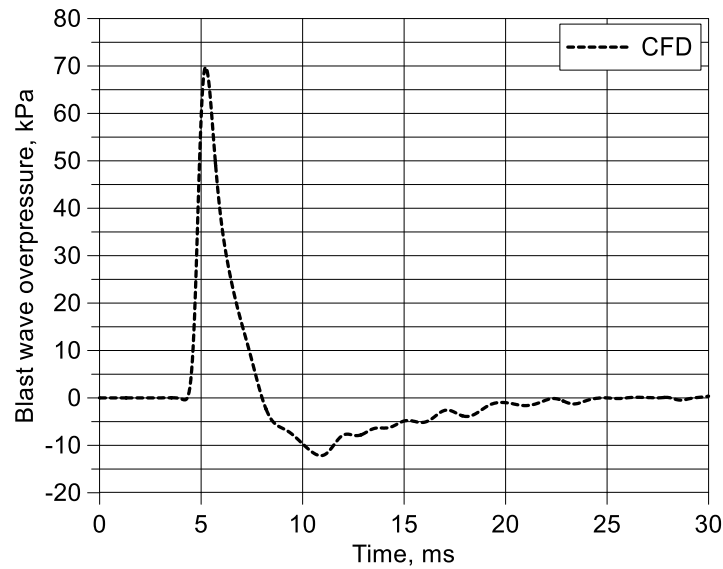


Effect of LH₂ filling ratio (FR)

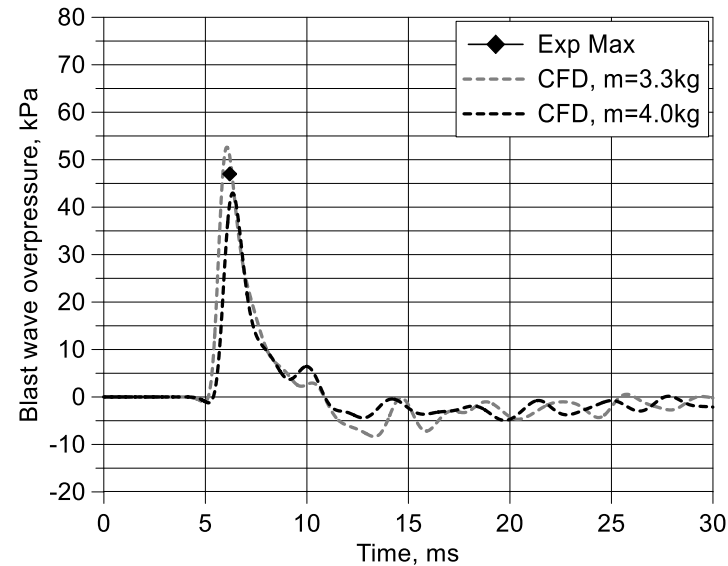
$P_s=1.1$ MPa(a)

Simulated overpressure at 3 m perpendicularly to the storage tank.

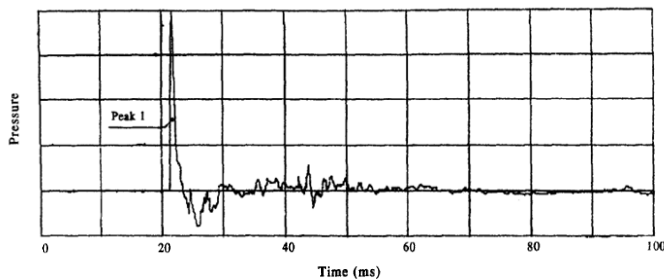
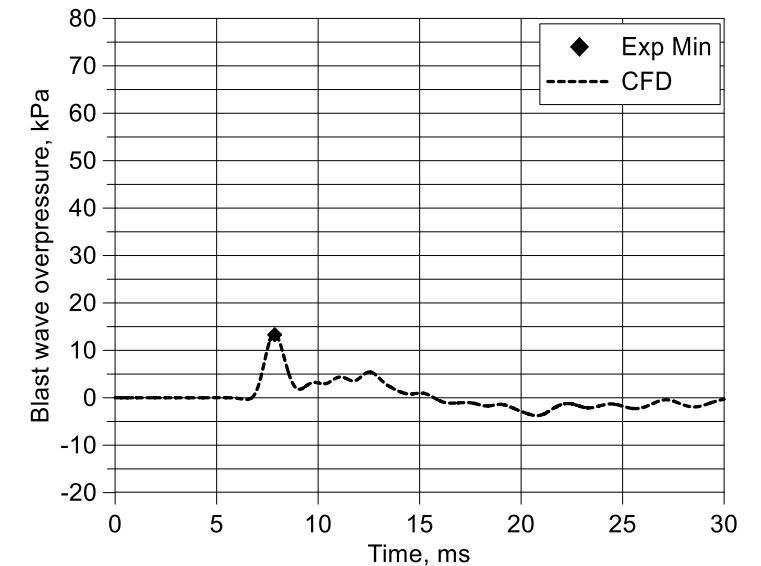
H₂ mass=2.0 kg (FR=0%)



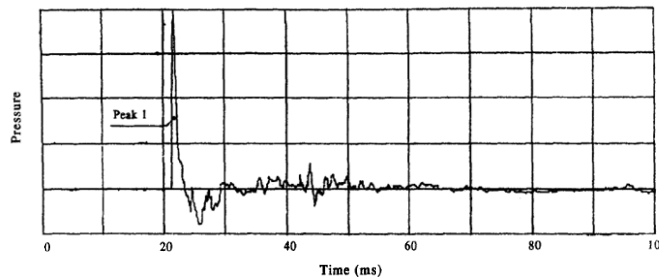
H₂ mass=3.3-4.0 kg (FR=45-55%)



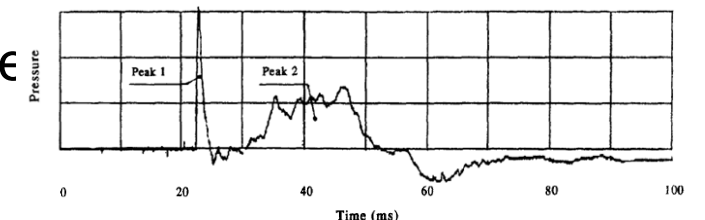
H₂ mass=5.4 kg (FR=93%)



Peak 1
incre



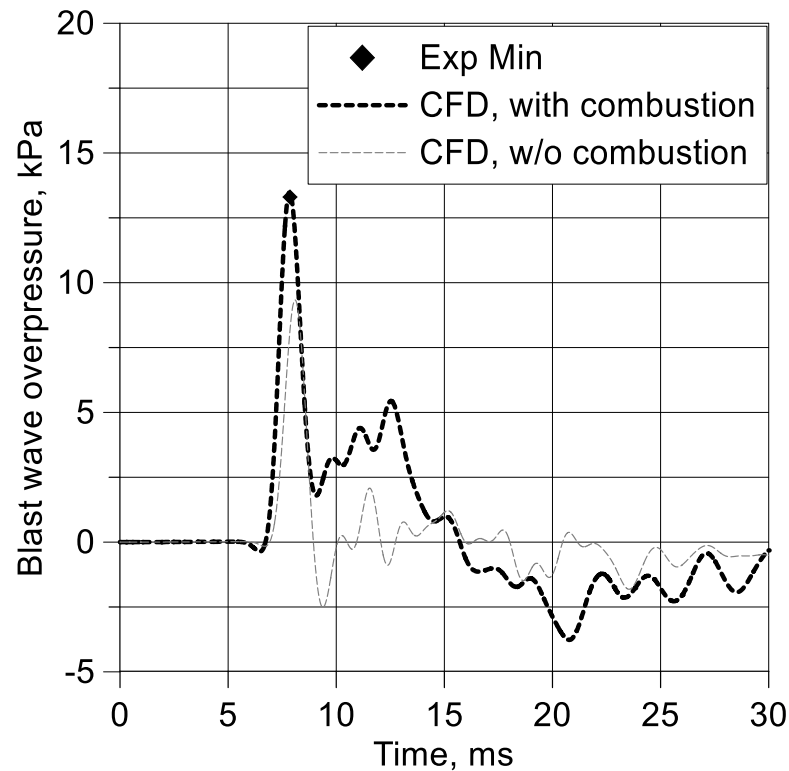
Peak 2, where
the pressure
increases.



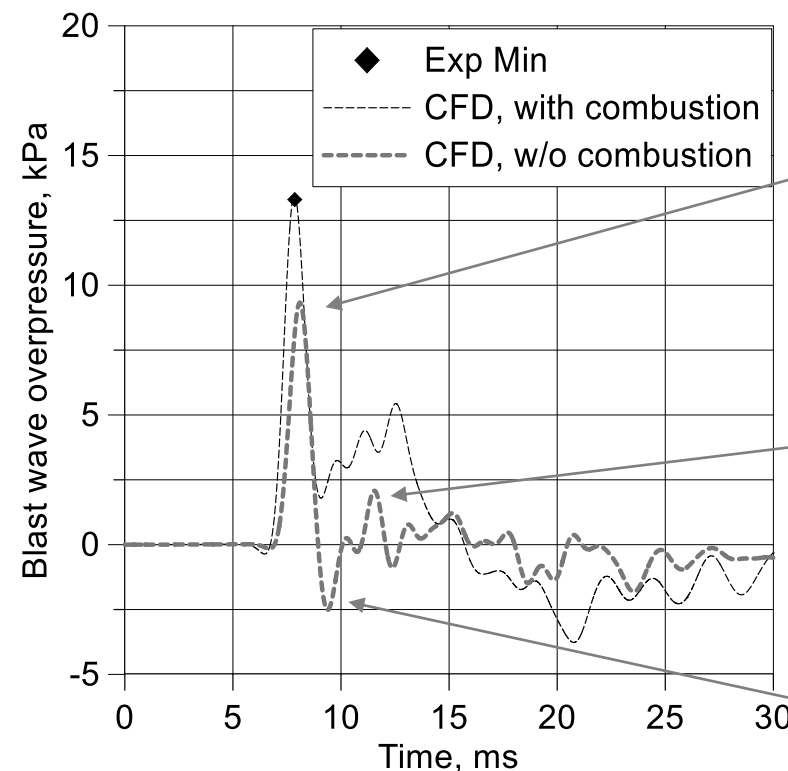
Effect of hydrogen combustion

$P_s=1.1$ MPa(a) and H_2 mass=5.4 kg

BLEVE with immediate ignition and combustion



BLEVE without immediate ignition and combustion



Peak 1: Starting shock from ullage gas explosion
-45% overpressure

Peak 2: LH_2 flash boiling blast. No combustion: less evaporation
-60% max overpressure
-65% impulse than peak 1

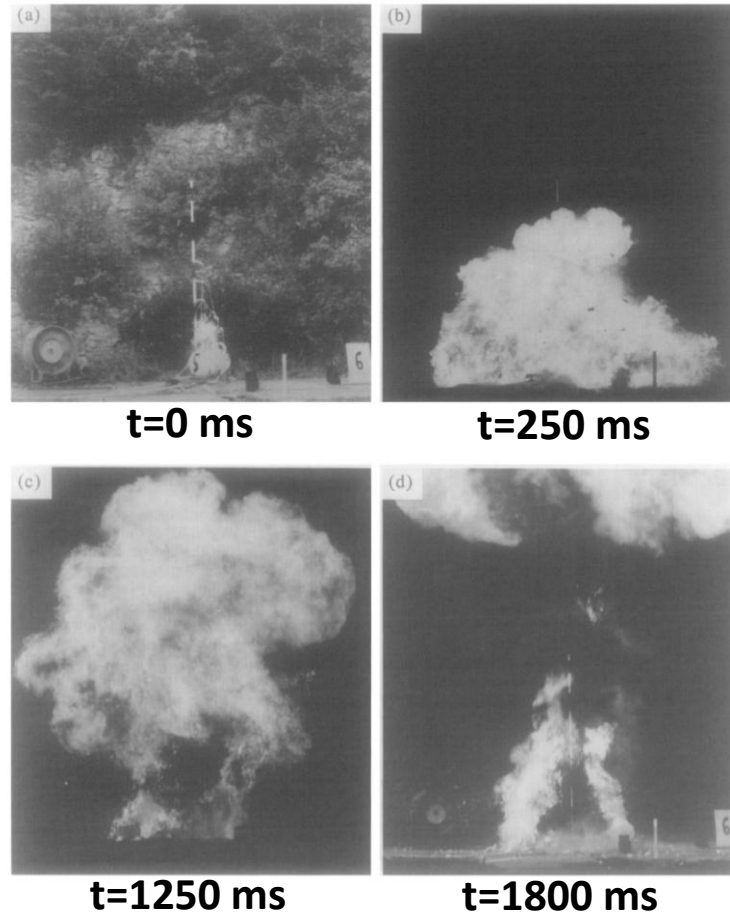
Presence of negative pressure phase

Combustion significantly contributes to the entire blast wave dynamics!

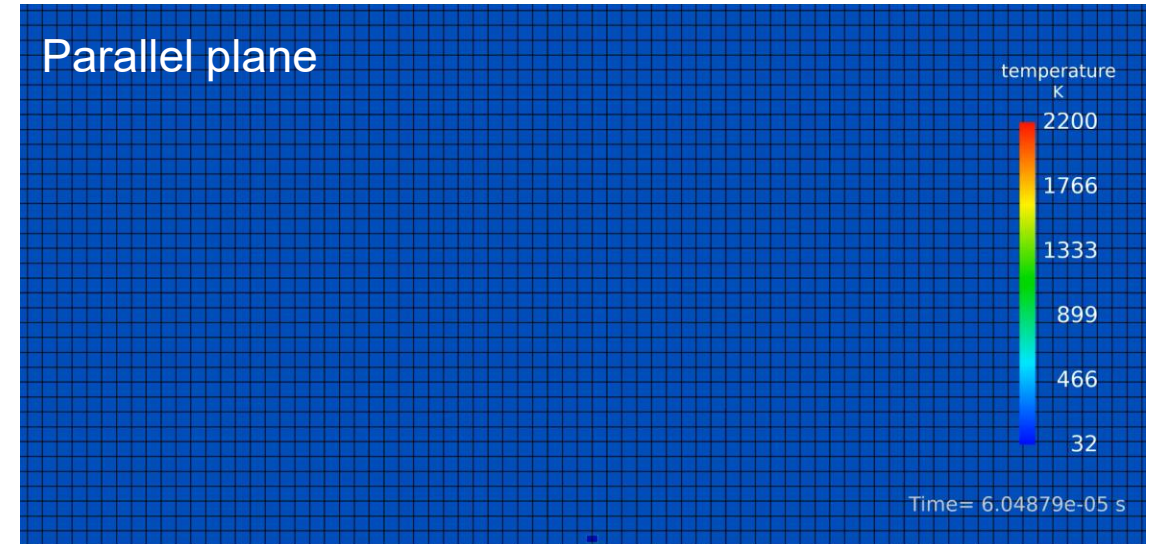
Fireball dynamics

$P_s=0.2$ MPa(a) and H_2 mass=5.4 kg

Fireball dynamics in experiments (Pehr, 1996)



Parallel plane



Perpendicular plane

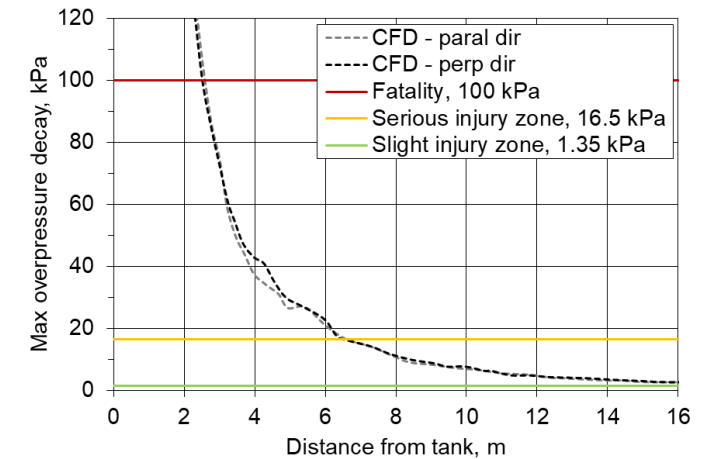


Hazard distances by pressure and thermal effects

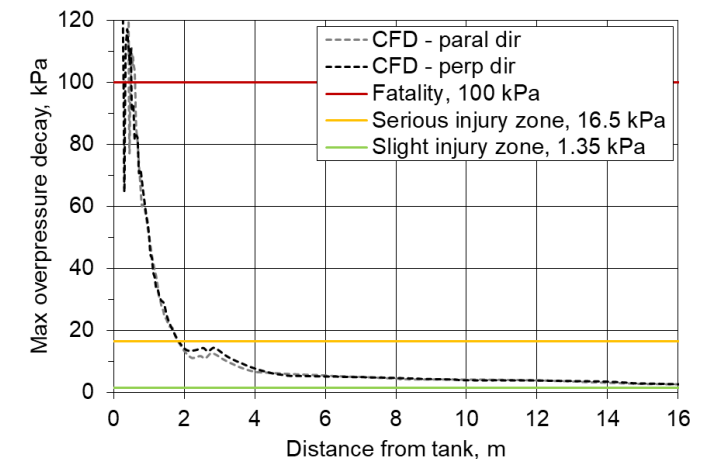
Assessment of entire blast wave and fireball dynamics and associated hazard distances:

- Hazard distances by pressure effects increase with CGH₂ fraction and burst pressure.
- Hazard distances by thermal effects decrease with increase of CGH₂ fraction, conversely to hazard distances by pressure effects.
- Hazard distances by thermal dose can be greater than those defined by pressure effects.
- The hazard distances defined by thermal effects for the BLEVE scenario with immediate combustion are observed to be greater than the flammable cloud extension.
- The LFL cloud is observed to persist significantly longer in time, increasing the duration of the incident and potential for delayed ignition of the flammable cloud.

Ps=1.1 MPa(a), H₂ mass=2.0 kg (FR=20%)



Ps=1.1 MPa(a), H₂ mass=5.4 kg (FR=93%)



Concluding remarks

- The CFD model can reproduce the multi-peak structure of blast wave and fireball observed in the BLEVE experiments performed earlier by BMW.
- It is demonstrated that the larger first pressure peak is generated by CGH₂ phase shock that is amplified by combustion at the contact surface between hydrogen and heated by shock air.
- The flash evaporation of the bulk liquid phase produces a series of secondary pressure waves smaller in amplitude of comparable impulse.
- The developed and validated CFD model can be used as a contemporary tool for hydrogen safety engineering and assessment of hazard distances for LH₂ storage tank BLEVE.
- A comprehensive assessment of BLEVE hazard distances shall account for both pressure and thermal hazards in case of immediate ignition and combustion, whose tendencies can shift according to the prevailing storage conditions.



Thank you for your attention

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Co-funded by
the European Union



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This research has received funding from the Clean Hydrogen Partnership under grant agreement No 101101381 (ELVHYS) and No 101137743 (DelHyVER). ELVHYS and DelHyVER projects are supported by the Clean Hydrogen Partnership (CHP) and its members. Co-funded by the European Union. University of Ulster in Horizon Europe Project ELVHYS is supported by UKRI grant number 10063519. DelHyVER is co-funded by the UK Research and Innovation and the Swiss Confederation.

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