CFD modelling of multi-peak blast wave structure of LH_2 storage tank BLEVE

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Introduction

- Transport and storage of liquid hydrogen (LH_2) is currently the most attractive option for scaling up the hydrogen supply infrastructure.
- LH_2 vacuum insulated tanks are equipped with pressure relief devices (PRD) to vent hydrogen and avoid the pressure build-up in a tank exchanging heat with the ambient, e.g. fire.
- If the PRD fails, or the structural integrity is compromised, the tank may fail with consequent blast wave, fireball and projectiles, as occurred in 1975 for a 76 m^3 LH_2 (Shen et al., 2024).
- A wide research was performed on hydrocarbon boiling liquid expanding vapour explosions (BLEVE), while there is a lack of knowledge for BLEVE occurrence for LH_2 storage systems.
- To the authors' knowledge, only two experimental studies on catastrophic rupture of LH_2 storage systems are available in literature:
    - BMW tests on "controlled rupture" of 0.12 m^3 LH_2 tank (Pehr, 1996).
    - SH2IFT tests on rupture of 1 m^3 LH_2 tank in a fire (van Wingerden et al., 2022).

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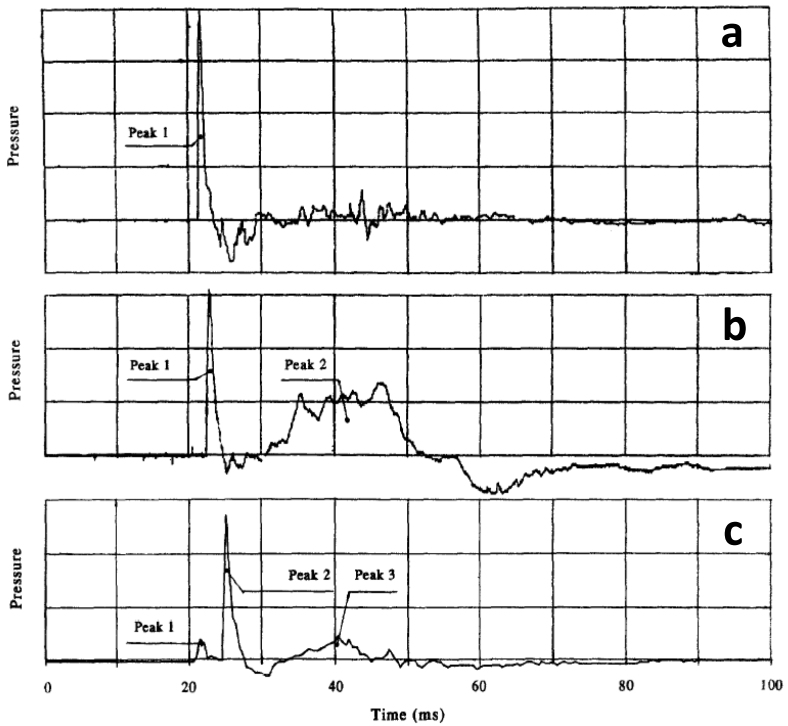
Real scale BMW experiments on BLEVE

- BMW experiments on the "controlled" rupture of LH_2 storage systems by an explosive charge.
- Stored H_2 mass varied in the range of 1.8-5.4 kg (0.12 m^3).
- Experimentalist explained pressure transients in Fig.(c) as:
  - Peak 1: explosive charge initiating the tank bursting.
  - Peak 2: pressure wave originated by the LH_2 evaporation and expansion of GH_2.
  - Peak 3: additional pressure event followed by the acceleration of flames and expansion of burnt gas behind the progressing flame front.



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

Test No.	1	2	3	4	5	6	7	8	9
Tank storage pressure, MPa abs	0.2	0.21	0.37	0.4	0.4	1.1	1.1	1.13	1.5
Blast overpressure at 3 m, kPa gauge	16.7	3.3	6.0	7.7	11.0	13.3	47.0	15.0	16.0

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Rethinking of “BLEVE” in BMW tests

Previous study in Cirrone et al. (2023) proposed a rethinking of the LH_2 storage tanks BLEVE overpressure transients observed in BMW tests:

- Peak 1: explosive charge.
- Peak 2: starting shock from the GH_2 phase enhanced by combustion at the contact surface with air.
- Peak 3: attributed to what is called BLEVE with probable contribution of the comparatively slow non-premixed combustion of hydrogen.

Development of a CFD approach to reproduce the blast wave maximum pressure by modelling the energy source associated to the GH_2 phase in the tank prior to rupture.


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Rethinking “BLEVE explosion” after liquid hydrogen storage tank rupture in a fire

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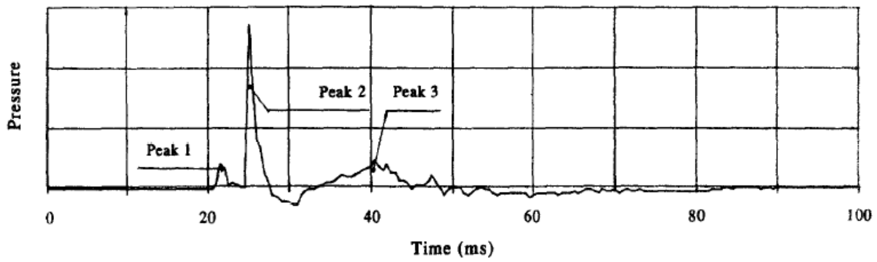

Typical pressure transients at 3 m from the tank centre with three distinctive peaks in BMW tests

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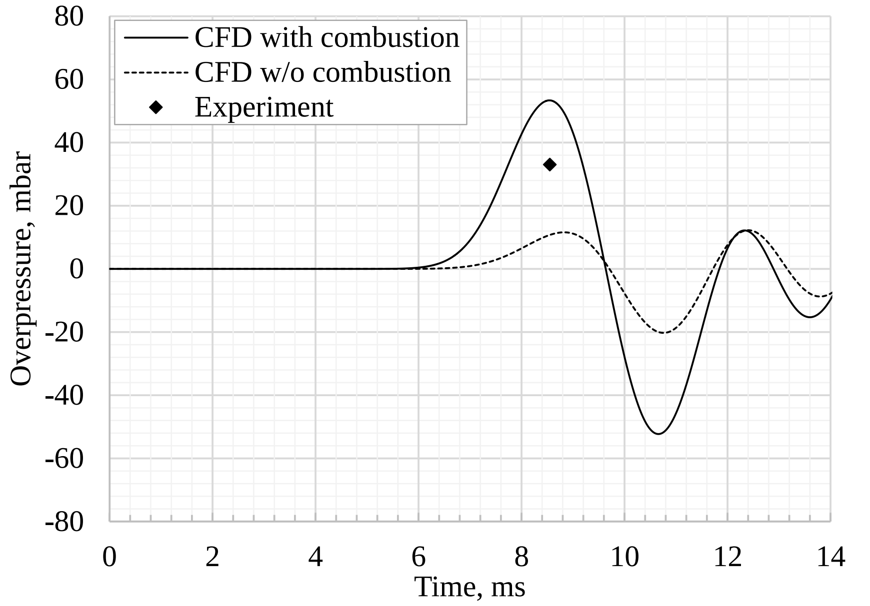
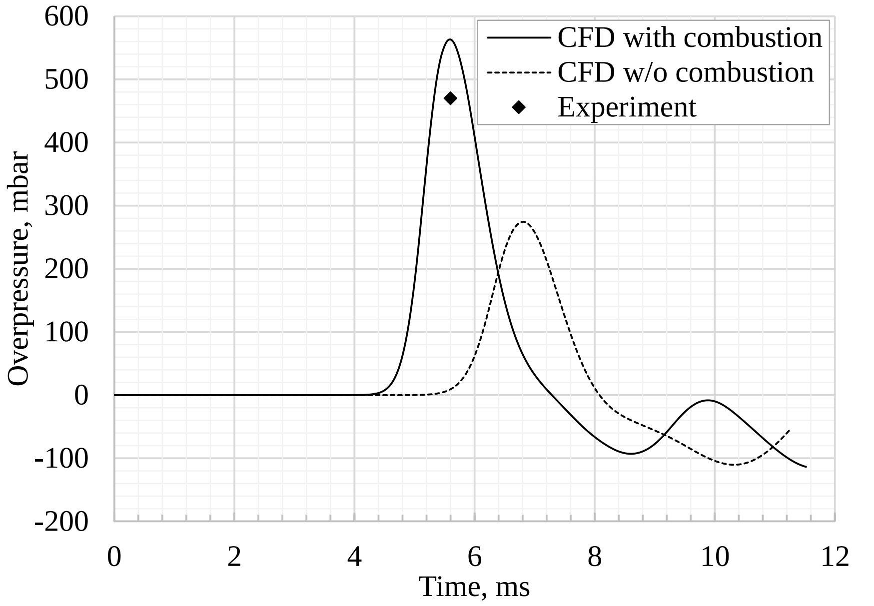
Results of CFD approach (2023)

- Simulated maximum overpressure was seen to increase with storage pressure and fraction of GH_2 in the tank prior to its rupture.
- Combustion significantly affects the maximum overpressure reached at 3 m. Effect increases for decreasing storage pressure.
- If combustion is not included in the CFD model, simulations would significantly underpredict experimental overpressure.



Overpressure at 3 m, P=0.21 MPa, m_{tot}≈5.4 kg



Overpressure at 3 m, P=1.1 MPa, m_{tot}≈5.4 kg

Need of an advanced CFD approach

There is a lack of well-established CFD methods that comprehensively account for all the physical processes involved in BLEVE of LH_2 storage systems to accurately estimate pressure and thermal effects. A comprehensive CFD approach shall fulfil the following requirements:

- Modelling of LH_2-GH_2 phase mass transfer to account for the effect of LH_2 evaporation on the overpressure dynamics beyond the shock overpressure peak generated by the vapour phase.
- Modelling of combustion to account for contribution of hydrogen reaction at the contact surface with air to the blast wave strength and assess the fireball and thermal hazards.
- Three-dimensional modelling to account for effect of directionality and complex geometries.

Scope of the research

The present research aims at the development of a novel three-dimensional comprehensive CFD approach that advances the model developed in 2023 to include the effect of evaporation of LH_2 phase in the tank on the blast wave pressure dynamics and reproduce the overpressure multi-peak structure of what is called “BLEVE” experimentally observed in BMW tests.

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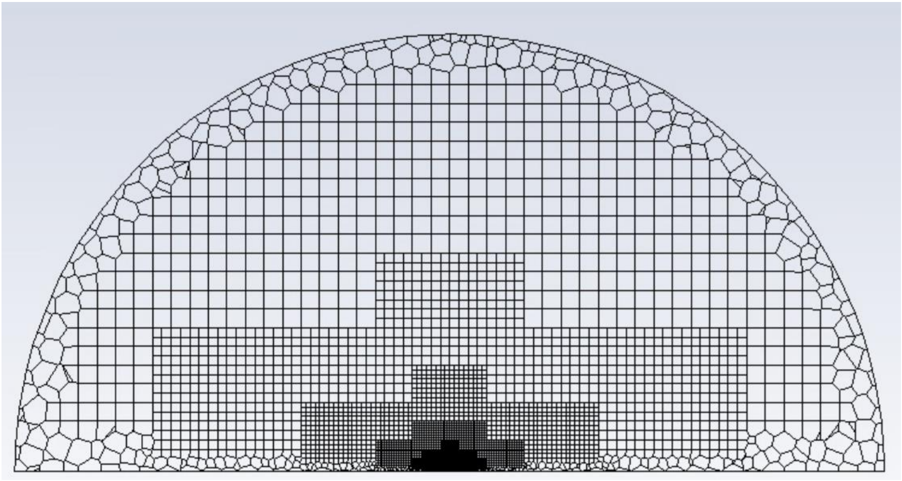
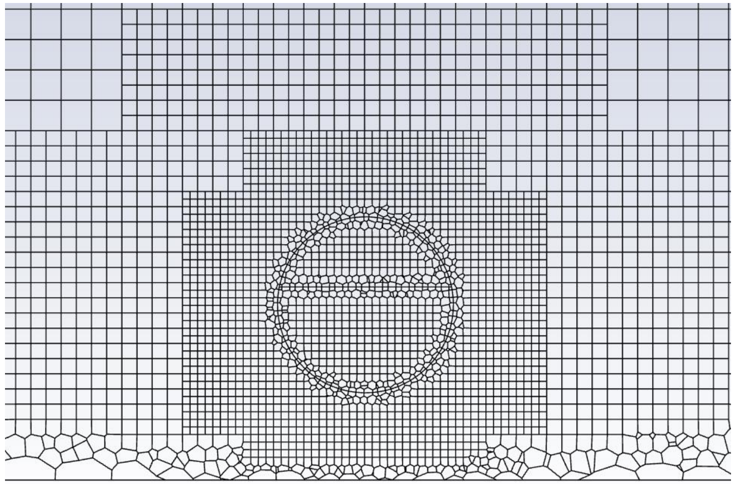
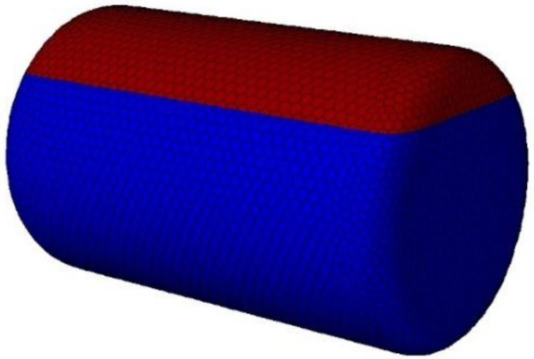
Numerical model and domain

- LES approach with Volume of Fluid for multiphase modelling.
- Finite Rate/Eddy Dissipation Model for combustion.
- The numerical domain is a poly-hexacore grid (400-700k CV).
- The approach in Cirrone et al. (2023) is adapted to the multiphase model to conserve the real gas internal energy stored in the GH_2 phase for modelling with ideal gas EoS.
- For each test pressure we assess the cases with min (**1.8 kg**) or max (**5.4 kg**) H_2 mass.

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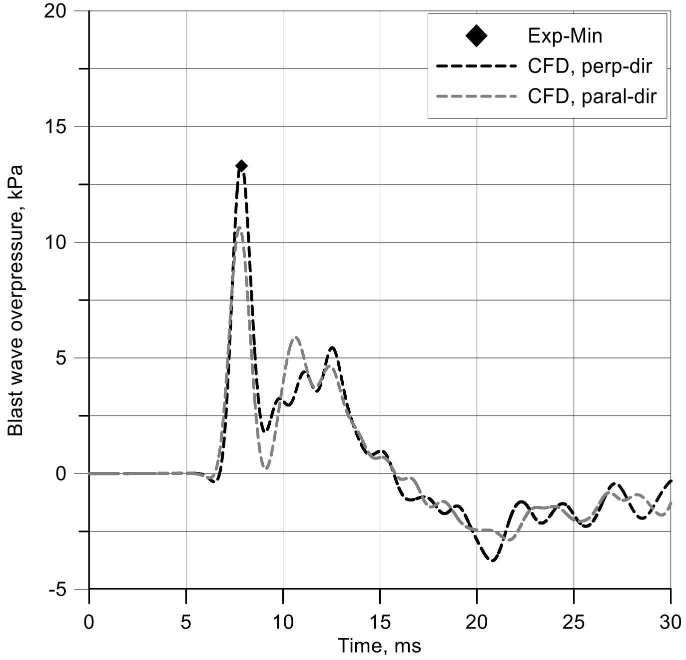
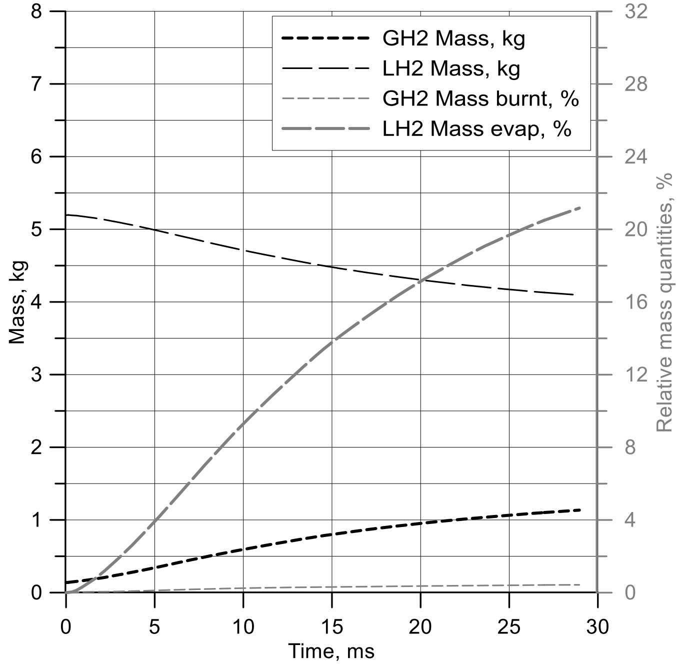
CFD simulation results

Overpressure dynamics, Ps=1.1 MPa

- Overpressure results for Ps=1.1 MPa and m_{tot}≈5.4 kg (Max LH_2 fraction).
- Maximum overpressure is higher in direction perpendicular to the tank axis.
- Overpressure first peak is associated with the gaseous phase shock fed by combustion.
- The series of secondary pressure peaks is associated to evaporation of LH_2.



Overpressure at 3 m

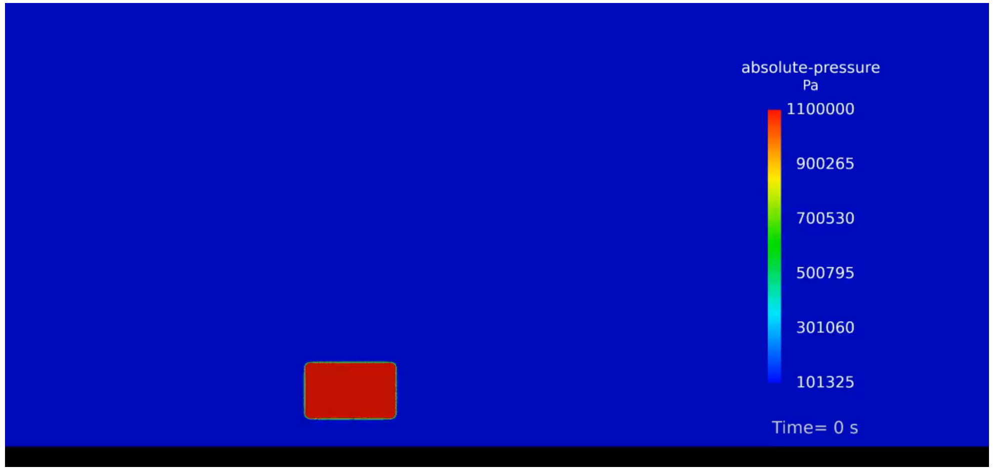


Dynamics of GH_2 and LH_2 masses

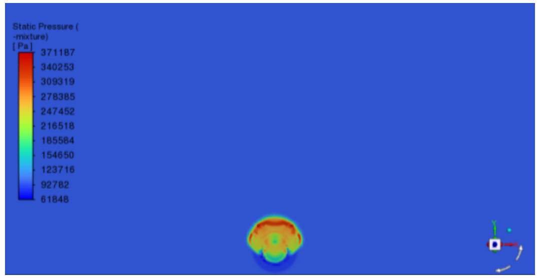
Blast wave and combustion dynamics (1/2)

- Case Ps=1.1 MPa, m_{tot}≈5.4 kg.

Pressure dynamics on z=0 plane



Temperature dynamics on z=0 plane



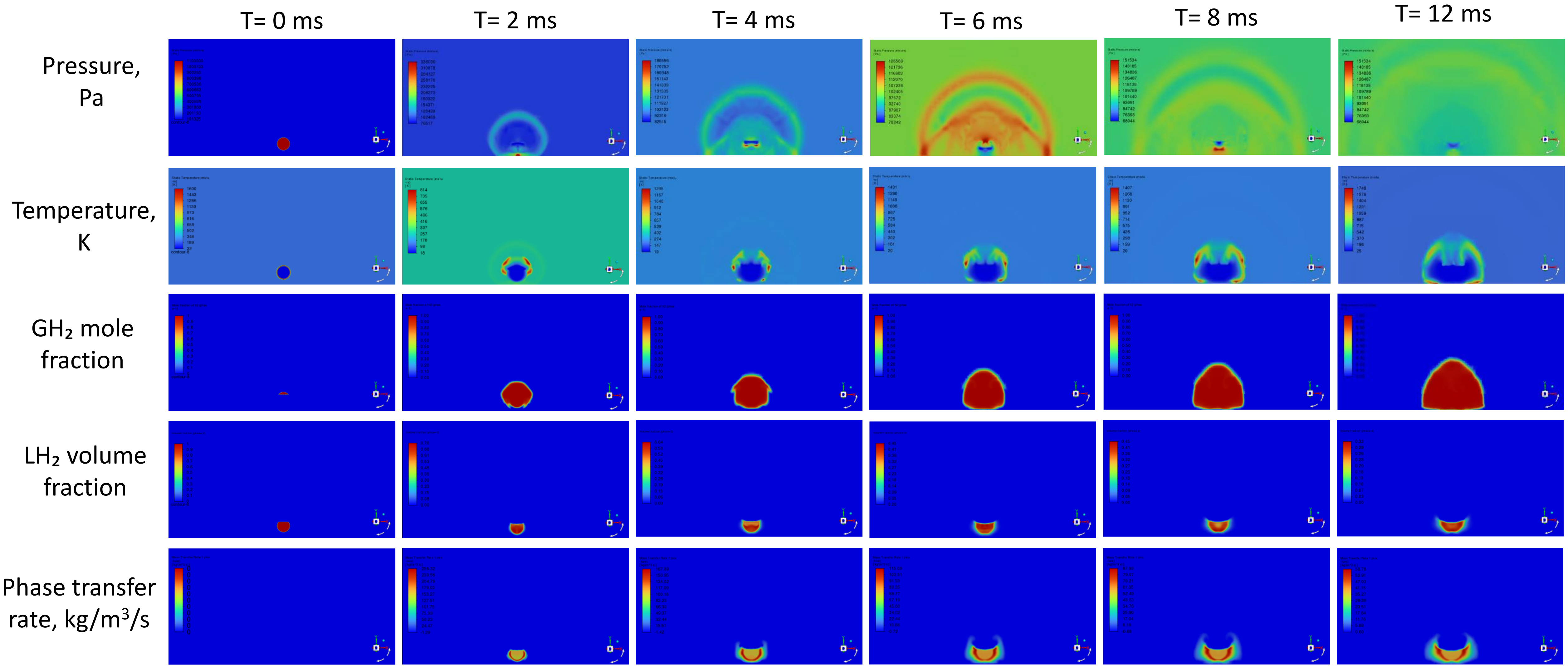
Pressure on x=0 plane at t=0.5 ms

Phase transfer dynamics on z=0 plane

Temperature on x=0 plane at t=0.5 ms

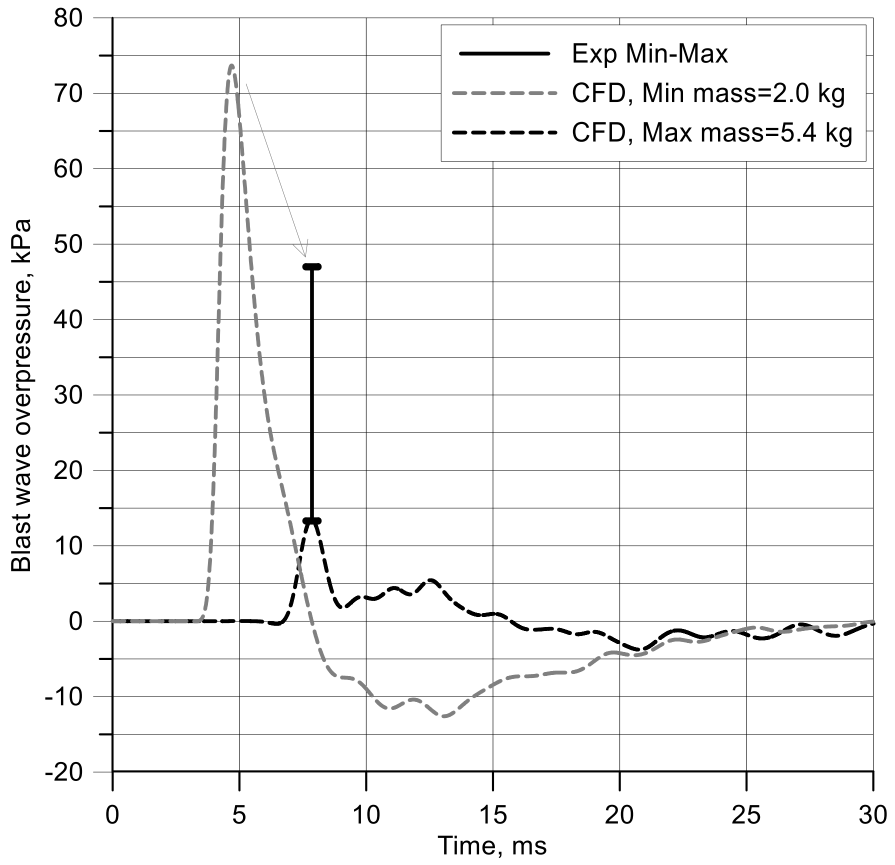
Blast wave and combustion dynamics (2/2)

- Case Ps=1.1 MPa, m_{tot}≈5.4 kg. Distributions on x=0 plane (perpendicular to the tank axis).

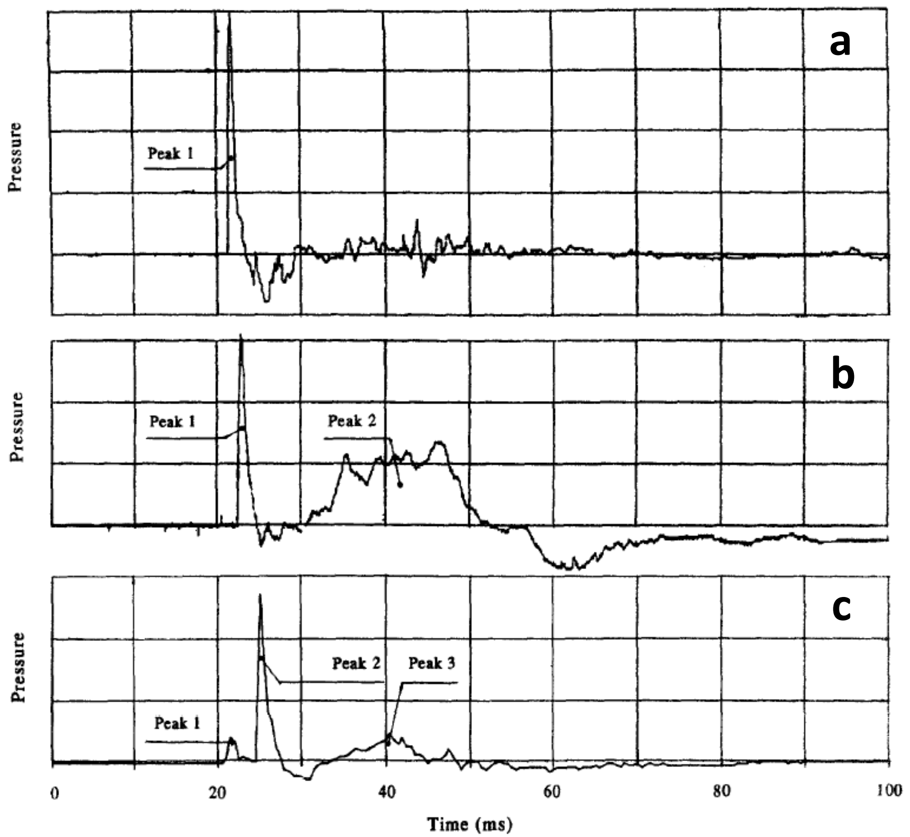


Overpressure dynamics, Ps=1.1 MPa

- Overpressure results for Ps=1.1 MPa for the limiting cases of stored mass equal to 2.0 kg (Max GH_2 fraction) and 5.4 kg (Max LH_2 fraction).



Overpressure at 3 m, P=1.1 MPa



Typical pressure transients in BMW tests

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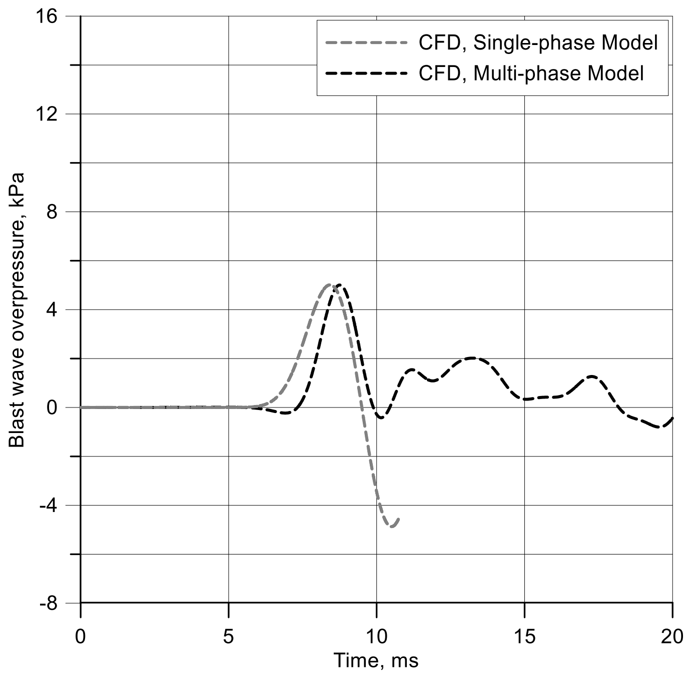
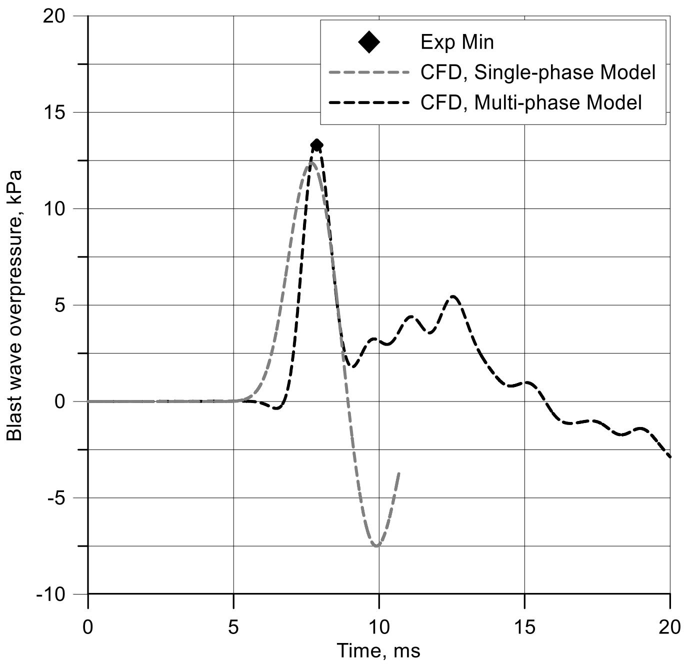
Advancement of the CFD approach

Comparison of overpressure simulated by:

- CFD, Single-phase Model: previous CFD approach developed in Cirrone et al. (2023).
- CFD, Multi-phase Model: advanced CFD approach with phase transition modelling.



Overpressure at 3 m, P=0.2 MPa, m_{tot}≈5.4 kg



Overpressure at 3 m, P=1.1 MPa, m_{tot}≈5.4 kg

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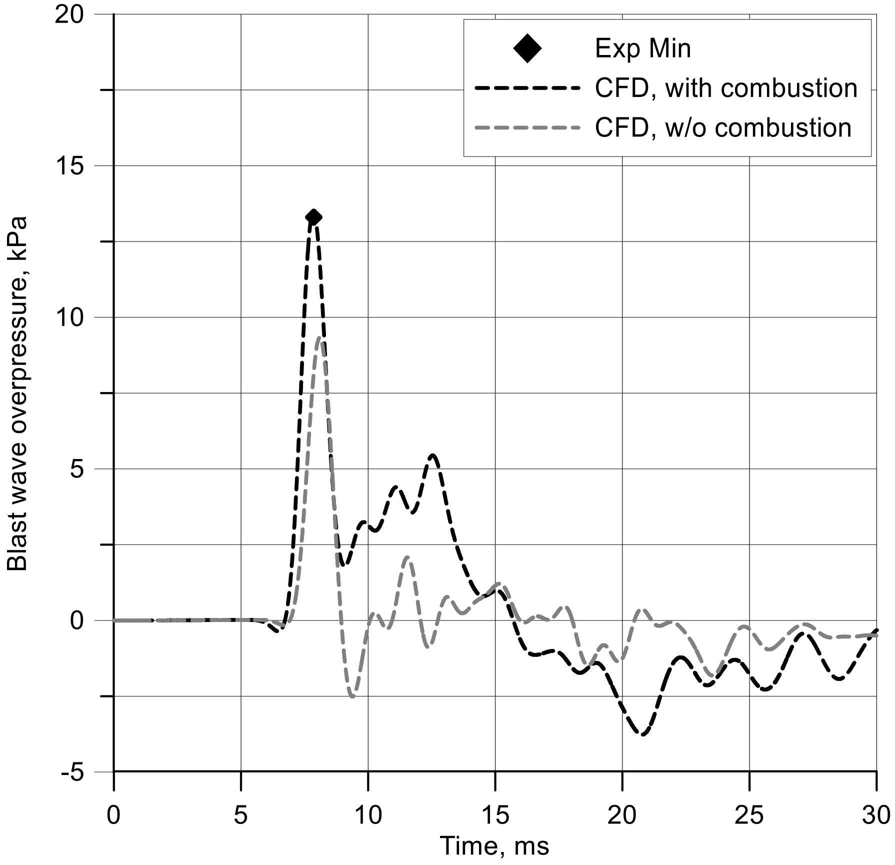
Effect of combustion contribution

- Overpressure results for Ps=1.1 MPa and m_{tot}≈5.4 kg (Max LH_2 fraction).

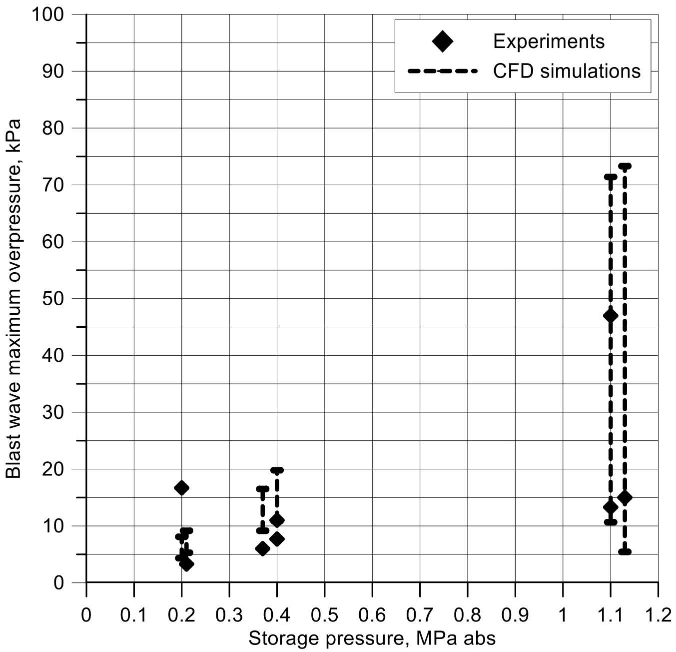
- Effect of combustion contribution to the blast wave strength:
  - 45% increase of the maximum overpressure peak generated by the GH_2 phase.
  - Absence of negative pressure phase after the first overpressure peak.
  - Faster secondary waves and more than twice larger maximum overpressure peak associated to the "BLEVE".



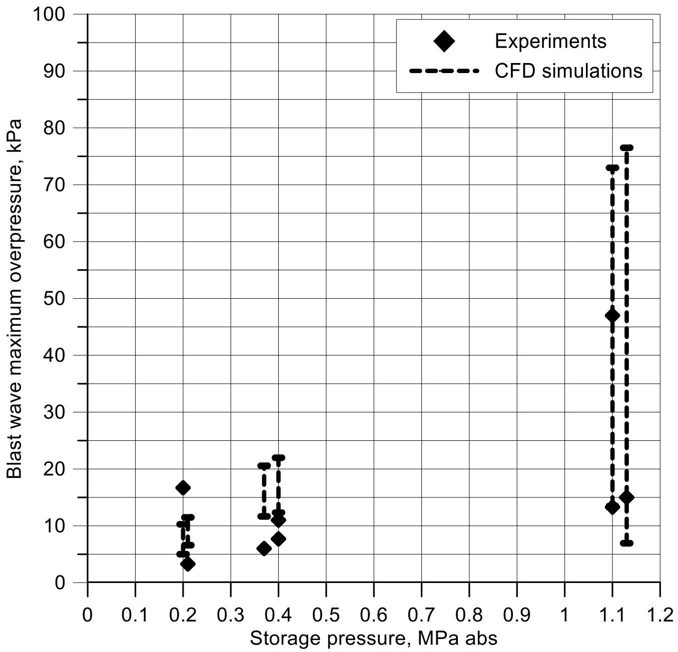
Overpressure at 3 m, P=1.1 MPa, m_{tot}≈5.4 kg

BLEVE modelling results VS BMW tests

- Simulations were carried out for the limiting cases corresponding to the possible minimum and maximum quantity of hydrogen mass in the tank for a given storage pressure.
- The CFD approach is able to reproduce the minimum and maximum experimental overpressures. A certain conservatism is due to neglecting mechanical energy losses on projectiles and ground cratering.
- Simulated maximum overpressure increases with the storage pressure and GH_2 volumetric fraction.



Overpressure at 3 m in parallel direction to the tank axis



Overpressure at 3 m in perpendicular direction to the tank axis

Research on BLEVE thermal hazards

- The maximum fireball diameter is calculated through correlation in Makarov et al. (2021) as:
  - $D_{f,bf}$=11.9-17.2 m for m= 1.8-5.4 kg
  - $D_{f,c}$=13.0-21.4 m for m= 1.8-5.4 kg
- Fireball estimates by the reduced model are in agreement with experimental measurements of D_f ranging from 6-15 m while on the ground, to up to 20 m after lift-off.
- The research findings suggest that employing liquid filling ratios as high as possible would limit the pressure hazards originated by the LH_2 tank rupture in a fire.
- However, pressure hazards should be counterposed by the thermal hazards.
- Further research should be performed towards modelling of a fireball and associated thermal hazards.

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Conclusions and future research

- The significance of the work lies in the advancement of the current understanding and modelling of the pressure multi-peak structure observed in BMW tests on BLEVEs of LH_2 storage systems.
- Findings suggest that the maximum blast wave pressure is generated by the gaseous phase starting shock enhanced by combustion reaction of hydrogen at the contact surface with air.
- The slower LH_2 evaporation process of the BLEVE produces a series of secondary pressure peaks with smaller amplitude but larger impulse.
- The release of chemical energy in the reaction of hydrogen with air contributes to the blast wave strength and dynamics also for the “BLEVE” phase.
- The simulations successfully reproduced BMW experimental maximum overpressure measured at 3 m from the storage tank.
- Future research on BLEVE should focus on:
  - Evaluation of a fireball and associated thermal hazards.
  - Experimental investigations for a deeper understanding of the phenomena and validation.

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Thank you for your attention

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