DOI: 10.13009/EUCASS2025-171
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

ANALYSIS OF THERMAL SLOSHING IN LH_2 TANKS THROUGH CFD-VOF SIMULATIONS

Ahmad Amani, Eugenio Schillaci, Carles Oliet†, and Jesus Castro
Heat and Mass Transfer Technological Center (CTTC), Universitat Politècnica de Catalunya (UPC)
08222 Terrassa, Spain, https://www.cttc.upc.edu
ahmad.amani@upc.edu · eugenio.schillaci@upc.edu · carles.oliet@upc.edu · jesus.castro@upc.edu
†Corresponding author

Abstract

Due to its high power density, the aviation sector is pushing towards its electrification by designing new propulsion systems based on cryogenic liquid hydrogen. From an engineering point of view, the efficient design of tanks constitutes one of the main challenges. They must guarantee efficient insulation of the fluid to avoid its evaporation and, at the same time, ensure reasonable weight and dimensions. Using numerical simulations is fundamental for studying heat transfer between the external environment and the liquid fuel, as well as possible pressure changes due to sloshing effects. In this work, a commercial CFD software is used to perform simulations adopting a Volume-of-Fluid interface tracking scheme coupled with the Lee mass transfer model. The analysis was conducted on a simplified 2D and a more realistic 3D tank geometry, exposed to various acceleration and sloshing processes, along with external heat fluxes.

1. Introduction

Due to its high power density, the aviation sector is pushing towards its electrification by designing new propulsion systems based on cryogenic liquid hydrogen (LH_2). From an engineering point of view, the efficient design of tanks constitutes one of the main challenges. They must guarantee efficient insulation of the extremely low-temperature liquid fuel to avoid its boiling-off and venting and ensure reasonable weight and dimensions to provide a competitive gravimetric index. In this context, the research community is currently seeking new LH_2 aircraft storage prototypes based on lightweight, innovative, and efficient concepts, ready to be integrated into the aircraft architecture for flight demonstrations at later stages. Hydrogen tanks will be subjected to highly variable conditions in terms of pressure and temperature and thermal sloshing effects, triggering drastic pressure changes from their liquid-vapor mixing occurrence. Using high-fidelity numerical simulations is fundamental for studying heat transfer between the external environment and the liquid fuel, as well as depressurization effects due to acceleration and sloshing events.

Mass transfer models Most works dealing with LH_2 evaporation processes are based on VOF or Level-Set methods developed within commercial software. A significant unknown is the approach employed for calculating the interface mass transfer. The most used model, available by default in commercial software, is the Lee equation, used in several works related to LH_2 tanks, such as Li et al.,[5] which focus on pressurization and temperature stratification when the tank is subjected to a fixed heat flux (101 W/m^2), and Jiang et al.,[6] which focuses on microgravity conditions and fixed temperature conditions for the shell. In Lee, the mass transfer rate is proportional to the difference between the local and saturation temperatures, driving the phase change process. The accommodation coefficient β, defined empirically, needs to be fine-tuned to match experimental data. However, other options have been developed as user-defined functions (UDFs); for example, the Schrage model is employed by Kartuzova et al.[7] (self-pressurization and cooling of the tank by liquid-spraying), Kassemi et al.[8] (analysis of interfacial turbulence and accommodation coefficient, low heat flux) and Stewart et al.[18] (pressurization of an MLI insulated tank subjected to 3.44 W/m^2 heat flux), while the Collier and Thome model is adopted by Shihao et al.[9] They analyzed the case of storage tanks for trailers (3D symmetry, 1/4 of the domain), measuring the effect on pressurization and thermal stratification of different filling levels and heat fluxes and introducing the effect of sloshing.

Dynamic and thermal sloshing numerical studies Multiphase models are widely employed for the analysis of sloshing phenomena. Here, we focus on the works dealing with thermal effects. The adopted sinusoidal sloshing

Copyright © 2025 by Amani et al. Published by the EUCASS association with permission.

DOI: 10.13009/EUCASS2025-171

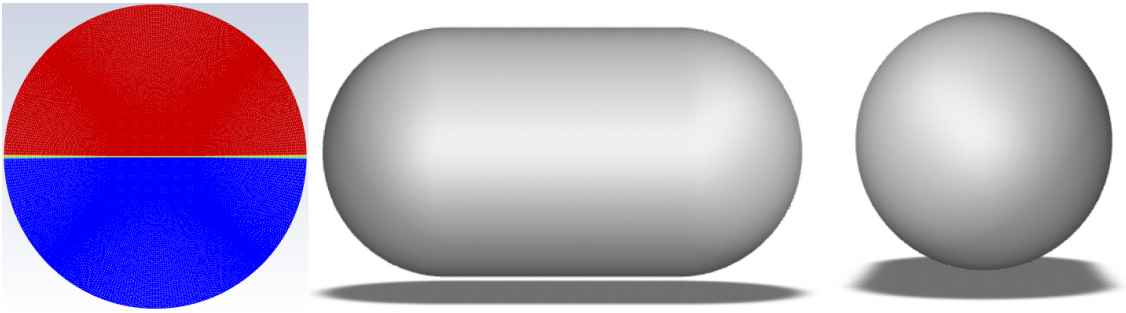

Figure 1: 2D (left) and 3D geometries used in this study, in particular, X-Y (middle) and Z-Y (right) lateral views.

excitation is usually expressed as:

$$\mathbf{x} = A\sin(2\pi f t) = A\sin(\omega t) \quad 0 < t < \tau_s \tag{1}$$

where $\mathbf{x}$ is the tank displacement, f is the oscillation frequency, ω is the angular frequency, A is the oscillation amplitude, and τ_s is the sloshing period, opposed to the holding period, during which the tank is not oscillating and the fluid keeps sloshing. Other important parameters to analyze are the acceleration g and the sloshing direction, usually horizontal x, or vertical, y. Grotle and Esoy[2] studied the thermodynamic response enhanced by sloshing inside liquefied natural gas (LNG) fuel tanks, using a modified version of an incompressible two-phase OpenFOAM solver to take into account the transport of thermal energy across the interface. Moreover, they performed experimental validation with water and LN_2 fluids. They performed sloshing cases with increasing oscillation frequency of the tanks (horizontal sloshing, $f = 0.29$ to 0.57 Hz). Simulations of multiphase flow including phase-change (mass transfer calculated by Lee model) and compressible flow physics, have been performed with Ansys Fluent, e.g., Liu et al.[11] analyzed a LO_2 fuel storage tank (made of 2219 Aluminium alloy) under different natural frequencies ($f = 0.51$ to 1.1 Hz). Different kinds of f, A, and τ_s are studied by the same authors in Liu et al.,[10] while in Liu et al.[12] they analyze fluid sloshing under different gravity acceleration levels, with g ranging from 1 to 4. Vertical excitation on liquid hydrogen sloshing in spacecraft storage tanks is analyzed by Hou et al.[4] ($f = 1$ to 30 Hz). Similar works apply to different kinds of storage concepts, both for static installations and vehicle transport. Between the others, Zhu et al.[20] focus on large-amplitude sloshing behavior of liquid hydrogen in a tank for heavy-duty trucks; a transverse sinusoidal acceleration with $f = 1.78$ Hz was set, exciting the tank during 0.448s. Zheng et al.[19] analyze the behavior of LH_2 insulated fuel tanks for a rocket during coastal periods (no phase change considered), thus setting a very specific profile in terms of g and oscillation, related to a rocket mission profile. Lv et al.[13] simulate large-scale liquid hydrogen tank with baffles under sloshing conditions (considering phase-change), adopting a sloshing profile coincident with that of Zhu et al.;[20] the impact of sloshing frequency was analyzed when introducing baffles ($f = 1$ to 4 Hz). Finally, in Ryali et al.,[15] the case of aeronautical tanks is studied to analyze the introduction of baffles to damp oscillations, employing Coupled Eulerian-Lagrangian (CEL) technique in ABAQUS (finite elements), thus, without considering phase change processes and the corresponding pressurization/depressurization. Overall, thermal sloshing studies are still lacking in the specific case of LH_2 tanks for commercial airliners (i.e., specific flight conditions), and, as expressed in the following paragraph, many other aircraft operations (e.g., related to the tank filling and LH_2 vaporization) still need detailed numerical simulations to allow full understanding of underlying phenomena.

Experimental activities Related to the validation of LH_2 dormancy cases, Aydelott[1] provided experimental tests for a spherical geometries and medium to high heat fluxes (50 to 230 W/m2), while Hasan et al.[3] provided tests with small heat fluxes and long dormancy times (lower than 3.5 W/m2). Relevant experimental tests for validation of sloshing depressurization scenarios have been performed by Moran et al.,[14] which shed new light on the response to various parameters of a cryogenic tanks (spherical shape) undergoing slosh, mainly in terms of pressurization rate and temperature profiles. The tests were performed with LH_2 and He, cover values of $f = 0.74$ Hz, $A = 1.5$ in and $f = 0.95$ Hz, $A = 0.5$ in, as well as different filling volumes, and consisted of an initial pressurization phase followed by a sloshing phase. The fluid sloshing experiments conducted by Grotle and Esoy[2] have been adopted to conduct model validation for pure sloshing cases by several authors. Currently, European projects are conducting experimental activities to enable effective validation of calculation tools for predicting pressure drop coming from thermal destratification, e.g., Saltari et al.[16]

Current work In this work, a commercial CFD software is used to perform multiphase flow simulations of sloshing phenomena within 2D– and 3D geometries to understand the underlying physical phenomena and quantify the effect

DOI: 10.13009/EUCASS2025-171

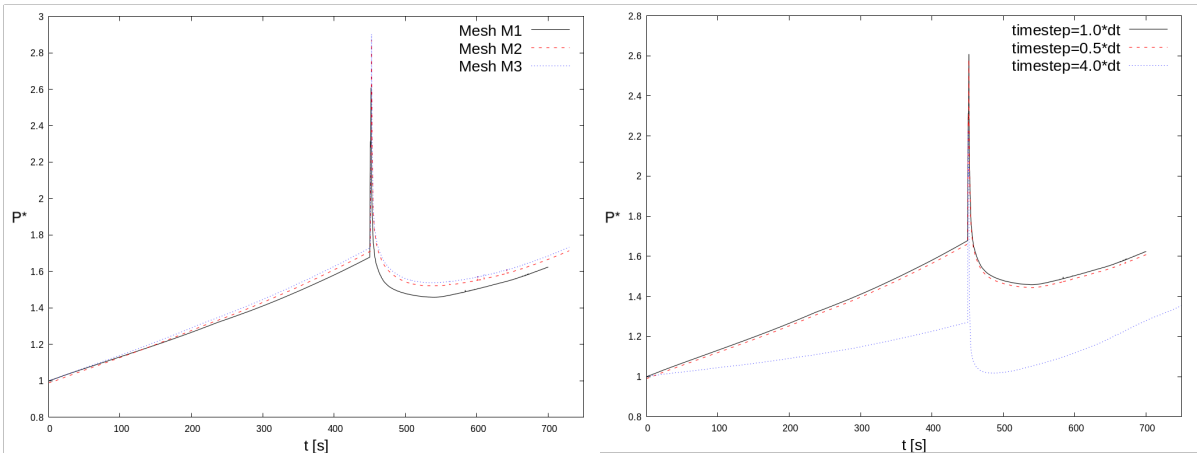

Figure 2: Domain 2D-a. Spatial (left) and temporal (right) convergence analysis for the pressure evolution in the 2D case with $d \simeq 1.0$ m, where a fixed heat flux of $\dot{q} = 150 W/m^2$ and acceleration of $g = 9.81\ m/s^2$ in x direction is set. The meshes M1, M2 and M3 refer to meshes with sizes of 30420, 60840 and 121680 cells, respectively, and timestep Δt is 0.01 s.

of different external conditions, e.g., in terms of heat fluxes and domain acceleration. The Volume-of-Fluid (VOF) approach, coupled with the Lee mass transfer model, is adopted. In a previous work,[17] the model was employed to study dormancy cases, i.e., the situation in which a static tank is subjected to a constant heat flux, thus experiencing progressive evaporation and internal pressurization. The model was tested to analyze some critical numerical parameters, such as the relaxation factor β, to provide information on the optimal values and compare the tank pressurization as a function of different external heat fluxes with the experimental reference from Aydelott[1] , thus validating its behavior. The current work employs the same numerical models to study the thermal sloshing scenario on a simplified 2D cylindrical domain and on a real tank 3D geometry. The simulations begin with a static dormancy case, leading to tank pressurization. At some point, the tank is subjected to acceleration due to a change in flight conditions, and a sudden fluid mixing is triggered. In some cases, the consequent thermal de-stratification leads to a sudden decrease in internal pressure, which can jeopardize the aircraft's propulsion operation. Different scenarios are analyzed in terms of external heat fluxes and acceleration forces (different **g** values are tested). Oscillation scenarios are examined as well, as different shaking frequencies are analysed. The results are post-processed, measuring pressure evolution and thermal stratification, thus leading to fundamental observations and conclusions regarding the cryogenic tank thermal behavior under sloshing scenarios.

2. Numerical models

The employed software is Ansys Fluent. The VOF model with the modified High-Resolution Interface Capturing (HRIC) convective scheme is selected to represent the two-phase flow interface. Different domains were employed:

- Two different 2D circular domains –reported in Fig. 1(left)– with the diameter d of $\simeq 1.0$ m (domain 2D-a) and 0.22 m (domain 2D-b), respectively. The mesh is fully structured, and different mesh sizes and time-steps were tested to verify spatial convergence (tests performed on the bigger domain). The latter domain is set to match the size of the spherical domain employed in the experimental work of Aydelott[1] , which was previously simulated by the authors in Schillaci et al.[17] , to perform validation in pressurization/dormancy tests and to calibrate the β parameter of the Lee model.
- A 3D domain –reported in Fig. 1(right)– reproducing a realistic tank geometry for the storage of cryogenic fluids. Mesh is fully unstructured and accounts for 730k tetrahedral elements. As a reference, the computational time for running 3D cases was 22 hours to simulate 60 seconds of physical time, using 40 Intel® Xeon® Gold 6230 CPUs of 2.1 GHz.

No turbulent modelization is employed in the momentum equations at this stage. A PISO scheme is used for the pressure-velocity Coupling, with fixed time steps; QUICK convective schemes are employed to solve momentum and energy, while the PRESTO! algorithm is employed for pressure resolution. The gas is considered ideal, while the Boussinesq model is employed to evaluate buoyancy effects in the fluid. Variations of properties with temperature and pressure are set using user-defined functions (UDF). For acceleration cases, different x-direction accelerations of

DOI: 10.13009/EUCASS2025-171

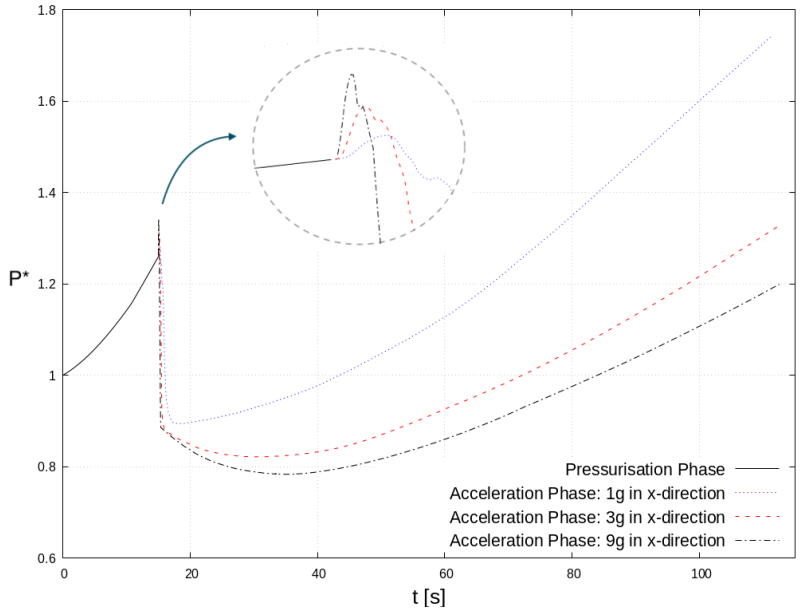

Figure 3: Domain 2D-b. Pressure change inside the domain during pressurization, as well as accelerating phase with $1g$, $3g$ and $9g$ in x direction.

$1g$, $3g$, and $9g$ values are tested. For oscillation cases, two time-dependent x-direction external acceleration terms as $g_x = 0.8326\sin(4.64t)$ and $g_x = 0.8326\sin(9.28t)$ were tested, extracted from the experimental work of Moran et al.[14]

3. Numerical results

The numerical tests performed in the current work correspond to different cases of pressurization scenarios followed by an acceleration or a sloshing phase. Pressure changes in time are represented in terms of P^*, which is defined as P/P_0 with P_0 as the total pressure inside the domain at $t = 0$ s.

3.1 2D domain - Spatial and temporal convergence

The spatial and temporal convergence are checked on domain 2D-a, which is left to pressurize at $\dot{q} = 150$ W/m^2. After 450 s, an acceleration of $1g$ in the x direction is set. The temperature field is initially uniform at $T = 20$ K. The tests are performed for different meshes with cell counts of 30420, 60840, and 121680 and different time-steps, in particular, $1.0\Delta t$, $0.5\Delta t$, and $4\Delta t$ where $\Delta t = 0.01$ s. The pressure inside the domain for the different mesh sizes and timesteps is reported in Fig. 2. All the cases show the same behavior, i.e., an initial constant-slope pressure rise, and the pressure drop as the gravitational acceleration is triggered. An instant pressure overshoot is identified; despite being observed in other works,[20] the authors currently do not have a clear explanation for this overshoot, and its analysis will deserve more attention in the future. Next, the pressure starts rising again with a pressurization rate close to that of the pure pressurization phase. The set-up with mesh size of 60840 cells and time-step=$1.0\Delta t$ is selected to perform the next simulations.

3.2 2D domain - Acceleration cases

In this test, performed on domain 2D-b, the tank is left to pressurize by fixing heat fluxes at the external walls. The conditions of Test 4 from Aydelott are set, i.e., $\dot{q} = 154 - 254$ W/m^2 (wet/dry), and initial filling of 48.9% for the pressurization phase. Next, the tank is shaken by a sudden change in acceleration g in the x-direction, and it is left to slosh under this effect. Three different acceleration cases are tested, spanning a wide range of possible events, i.e., acceleration with $1g$, $3g$, and $9g$.
The evolution of pressure with time for the three different cases is reported in Fig. 3. In the initial part, pressurization occurs. At a certain point, the acceleration starts, leading to an overshoot and a sudden drop due to thermal destratification. From that moment, the tank begins to pressurize again, with a less pronounced pressurization rate for the higher gravitational accelerations.

DOI: 10.13009/EUCASS2025-171

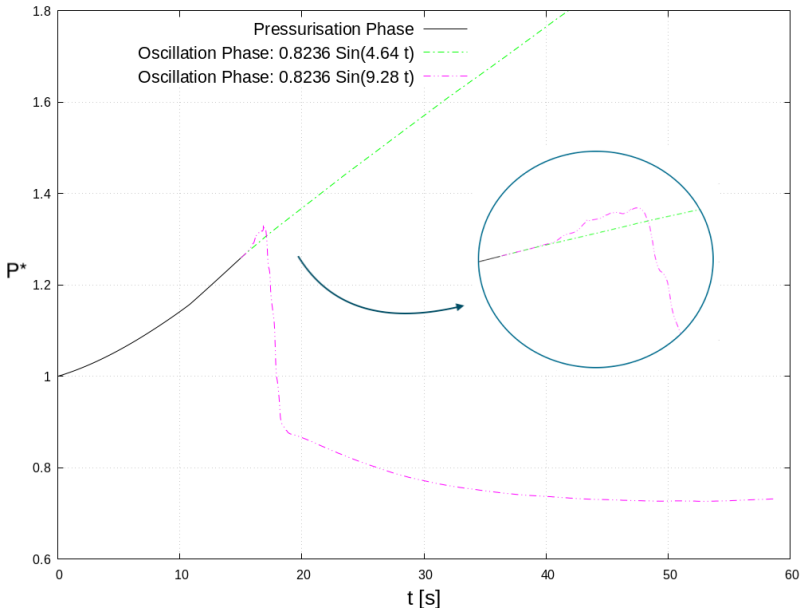

Figure 4: Domain 2D-b. Pressure change inside the domain during pressurization, as well as sloshing phase with $g_x = 0.8326\sin(4.64t)$ and $g_x = 0.8326\sin(9.28t)$.

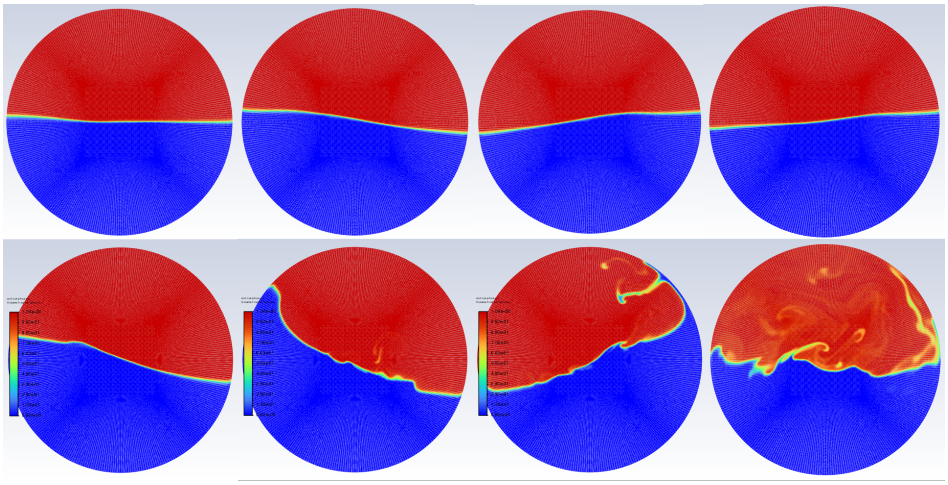

Figure 5: Domain 2D-b. Interface contours from left to right at: 4, 5, 6 and 9 seconds after starting sloshing phase with (top) $g_x = 0.8326\sin(4.64t)$ and (bottom) $g_x = 0.8326\sin(9.28t)$.

DOI: 10.13009/EUCASS2025-171

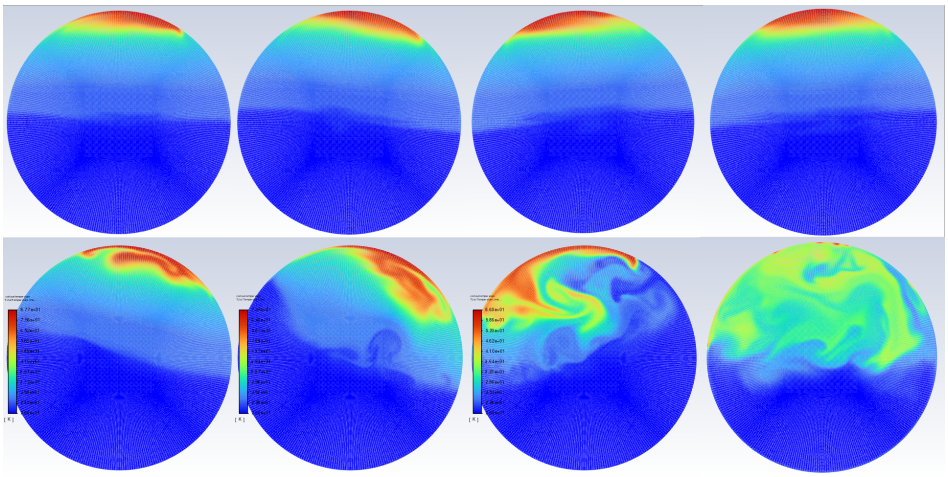

Figure 6: Domain 2D-b. Temperature contours from left to right at: 4, 5, 6, and 9 seconds after starting sloshing phase with (top) $g_x = 0.8326 \sin(4.64t)$ and (bottom) $g_x = 0.8326 \sin(9.28t)$.

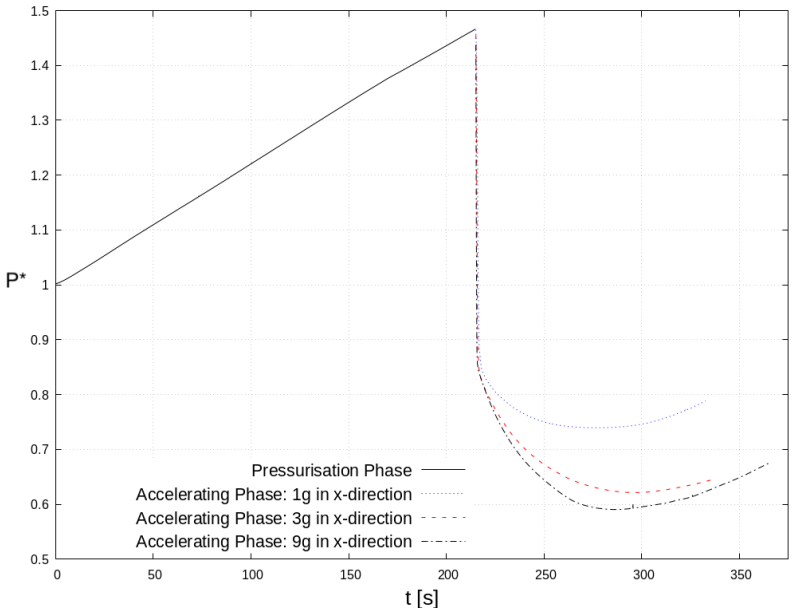

Figure 7: Domain 3D. Pressure change inside the domain during pressurization, as well as sloshing phase with $1g$, $3g$ and $9g$ in x-direction for test case with $\dot{q} = 150\ W/m^2$.

DOI: 10.13009/EUCASS2025-171

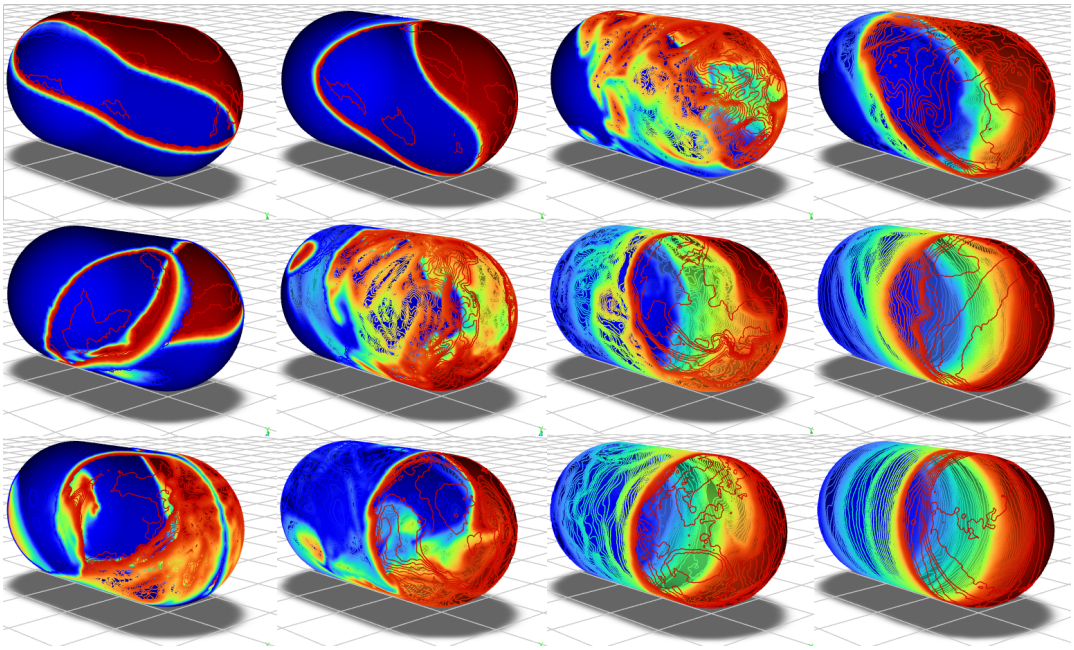

Figure 8: Domain 3D. Interface contours from left to right at: 0.4, 0.9, and 3 and 9 seconds after $1g$ (top), $3g$ (middle), and $9g$ (bottom) x-direction acceleration for test case with $\dot{q} = 150\ W/m^2$.

3.3 2D domain - Oscillation cases

In these cases, also performed on domain 2D-b, after the initial pressurization phase where the tank is subjected to the fixed heat fluxes (condition from Test 4 of Aydelott), a constant oscillation is set along the x-direction, following the laws introduced in Sec. 2. The evolution of pressure with time is reported in Fig. 4, while interface contours are depicted in Fig. 5. The case with the lower oscillation frequency continues to pressurize even after the shaking has started, while the cases with the higher frequency experience a strong pressure drop, followed by a flat evolution pressure profile in the simulated time-frame. This can be explained by the temperature maps shown in Fig. 6, which clearly depict how in the first case no temperature de-stratification is triggered, while in the second case a strong mixing of the gas phase occurs (even having a non-completed mixing), leading to the pressure loss.

3.4 3D domain - Acceleration cases

In this test, performed on domain 3D, the tank is left to pressurize by fixing a heat flux of $\dot{q} = 150\ W/m^2$ at the external walls, and initial filling of 50%. The static pressurization phase lasts around 220 s. Next, the tank is shaken by a sudden change in the x-direction acceleration. Three different values for accelerations are tested, spanning a wide range of possible events, i.e., $1g$, $3g$, and $9g$.
The evolution of pressure with time for the three different cases is depicted in Fig. 7. In the initial part, pressurization occurs. At a certain point, the acceleration is triggered, leading to a sudden drop due to thermal destratification. A pressure overshoot is not observed for 3D cases. From that moment, the tank begins to pressurize again, with a less pronounced pressurization rate for the higher gravitational accelerations. Fig. 8 illustrates the interface contours for different times after the start of the acceleration. The mixing process is clearly influenced by acceleration in each instance observed, as depicted in the temperature maps of Fig. 9.

3.5 3D domain - Oscillation cases

Oscillation cases are also performed on the 3D domain. After the initial pressurization phase with fixed $\dot{q} = 150\ W/m^2$, a constant oscillation is set along the x-direction, following the laws introduced in Sec. 2. The evolution of pressure with time is reported in Fig. 10. The two cases show a pressure drop when the fluctuation is triggered. The pressure starts recovering again after the shaking starts, with a faster increase in the lower frequency simulation.

DOI: 10.13009/EUCASS2025-171

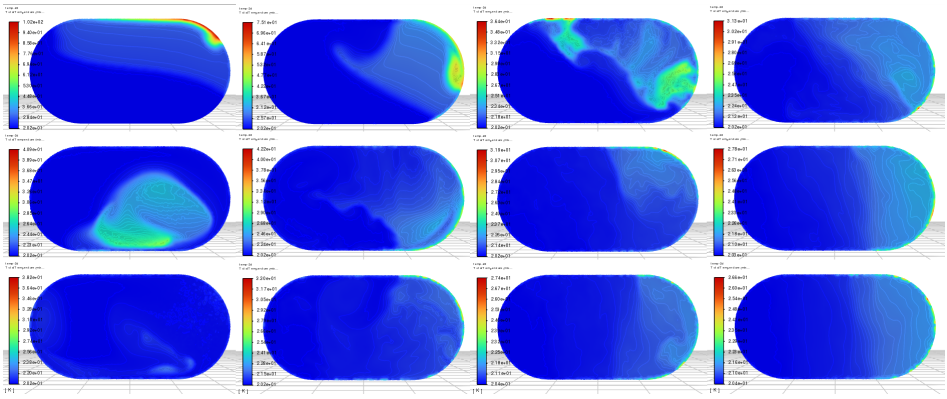

Figure 9: Domain 3D. Temperature contours from left to right at: 0.4, 0.9 and 3, and 9 seconds after $1g$ (top), $3g$ (middle) and $9g$ (bottom) x-direction acceleration for test case with $\dot{q} = 150\ W/m^2$.

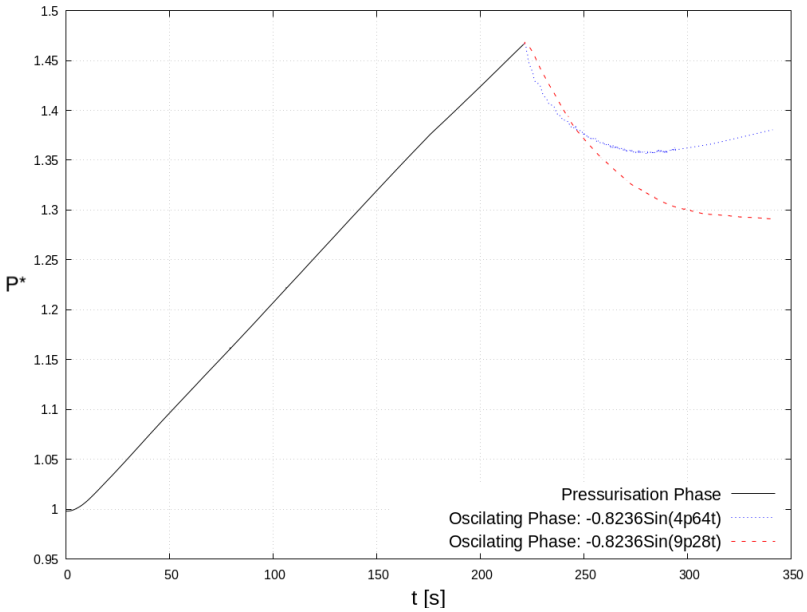

Figure 10: Domain 3D. Pressure change inside the domain during pressurization, as well as sloshing phase with $g_x = 0.8326\sin(4.64t)$ and $g_x = 0.8326\sin(9.28t)$ in x direction for test case with $\dot{q} = 150W/m^2$.

DOI: 10.13009/EUCASS2025-171

4. Conclusion

This work presents a comprehensive numerical investigation of thermal sloshing phenomena in cryogenic tanks using a Volume-of-Fluid (VOF) approach coupled with the Lee mass transfer model. Simulations were performed in both 2D and 3D geometries, analyzing the behavior of LH_2 under varying external conditions, including fixed and oscillating accelerations, and different heat flux inputs. The results confirm that those dynamic conditions can lead to significant thermal de-stratification within the tank, which in turn causes sudden pressure drops that may compromise tank stability and, in aerospace applications, the reliability of propulsion systems. Key findings from the study include:

- Demonstration of mesh and timestep independence in 2D simulations, ensuring robustness of the numerical setup;
- Observation that higher accelerations cause more intense mixing and slower pressure recovery due to enhanced thermal homogenization;
- Identification of frequency-dependent effects in oscillating scenarios, where different-frequency shaking leads to pressure drops associated with increased phase mixing;
- Extension of the analysis to realistic 3D geometries, revealing similar qualitative behaviors as in 2D, though with some differences, such as the absence of pressure overshoots.

These results can inform the design and operation of storage systems in aerospace applications, where understanding and mitigating sloshing-induced pressure fluctuations is critical. Future work will aim at refining the understanding of some numerical instabilities, incorporating turbulence models, and validating additional 3D cases with experimental benchmarks.

5. Acknowledgments

Carles Oliet, as a Serra-Húnter Associate Professor, acknowledges the Catalan Government for the support through this Programme.

References

[1] John C Aydelott. Normal gravity self-pressurization of 9-inch-/23 cm/diameter spherical liquid hydrogen tankage. Technical report, National Aeronautics and Space Administration, 1967.

[2] Erlend Liavåg Grotle and Vilmar Æsøy. Numerical simulations of sloshing and the thermodynamic response due to mixing. *Energies*, 10(9):1338, 2017.

[3] MM Hasan, Cheng S Lin, and NT Vandresar. Self-pressurization of a flightweight liquid hydrogen storage tank subjected to low heat flux. In *1991 ASME/AIChE National Heat Transfer Conference*, number E-6095, 1991.

[4] Chaoran Hou, Yusong Yu, Xiaodan Liu, Jiawei Ding, and Zhifeng Cui. Effects of longitudinal excitation on liquid hydrogen sloshing in spacecraft storage tanks under microgravity conditions. *International Journal of Hydrogen Energy*, 51:765–780, 2024.

[5] LI Jiachao and Guozhu Liang. Simulation of mass and heat transfer in liquid hydrogen tanks during pressurizing. *Chinese Journal of Aeronautics*, 32(9):2068–2084, 2019.

[6] Yaobin Jiang, Yusong Yu, Zheng Wang, Shurui Zhang, and Jie Cao. Cfd simulation of heat transfer and phase change characteristics of the cryogenic liquid hydrogen tank under microgravity conditions. *International Journal of Hydrogen Energy*, 48(19):7026–7037, 2023.

[7] Olga V Kartuzova and Mohammad Kassemi. Cfd modeling of the multipurpose hydrogen test bed (mhtb) self-pressurization and spray bar mixing experiments in normal gravity: effect of the accommodation coefficient on the tank pressure. In *51st AIAA/SAE/ASEE joint propulsion conference*, page 3769, 2015.

[8] Mohammad Kassemi and Olga Kartuzova. Effect of interfacial turbulence and accommodation coefficient on cfd predictions of pressurization and pressure control in cryogenic storage tank. *Cryogenics*, 74:138–153, 2016.

DOI: 10.13009/EUCASS2025-171

[9] Shihao Li, Yan Yan, Wei Wei, Zhao Wang, and Zhonghua Ni. Numerical simulation on the thermal dynamic behavior of liquid hydrogen in a storage tank for trailers. *Case Studies in Thermal Engineering*, 40:102520, 2022.

[10] Zhan Liu, Yuyang Feng, Jie Cui, Gang Lei, and Yanzhong Li. Effect of excitation types on sloshing dynamic characteristics in a cryogenic liquid oxygen tank. *Journal of Aerospace Engineering*, 32(6):04019096, 2019.

[11] Zhan Liu, Kaifeng Yuan, Yuanliang Liu, Martin Andersson, and Yanzhong Li. Fluid sloshing hydrodynamics in a cryogenic fuel storage tank under different order natural frequencies. *Journal of Energy Storage*, 52:104830, 2022.

[12] Zhan Liu, Kaifeng Yuan, Yuanliang Liu, Yinan Qiu, and Gang Lei. Fluid sloshing thermo-mechanical characteristic in a cryogenic fuel storage tank under different gravity acceleration levels. *International Journal of Hydrogen Energy*, 47(59):25007–25021, 2022.

[13] Hongyu Lv, Liang Chen, Ze Zhang, Shuangtao Chen, and Yu Hou. Numerical study on thermodynamic characteristics of large-scale liquid hydrogen tank with baffles under sloshing conditions. *International Journal of Hydrogen Energy*, 57:562–574, 2024.

[14] Matthew E Moran, Nancy B McNelis, Maureen T Kudlac, Mark S Haberbusch, and George A Satornino. Experimental results of hydrogen slosh in a 62 cubic foot (1750 liter) tank. In *Joint Propulsion Conference*, number E-8916, 1994.

[15] L Ryali, W Stautner, and D Mariappan. Impact of internal baffle designs on liquid hydrogen sloshing in cryogenic aircraft fuel tanks. In *IOP Conference Series: Materials Science and Engineering*, volume 1301, page 012068. IOP Publishing, 2024.

[16] Francesco Saltari, Marco Pizzoli, Mario Tindaro Migliorino, Antonello Binni, Giuliano Coppotelli, Franco Mastroddi, Tiziano Pagliaroli, Fabio Del Duchetto, Francesco Gambioli, Ramon Abarca, et al. Experimental investigations on the sloshing-induced pressure drop in tanks for hydrogen-powered aircraft. In *AIAA SCITECH 2024 Forum*, page 2158, 2024.

[17] Eugenio Schillaci, Ahmad Amani, Carles Oliet, Joaquim Rigola, and Jesus Castro. Calibration and verification of cfd-vof models for the analysis of pressurization scenarios in lh2 tanks. In *Journal of Physics: Conference Series*, volume 2766, page 012041. IOP Publishing, 2024.

[18] Mark Stewart and Jeffrey P Moder. Self-pressurization of a flightweight, liquid hydrogen tank: Simulation and comparison with experiments. In *52nd AIAA/SAE/ASEE joint propulsion conference*, page 4674, 2016.

[19] Zhaoqi Zheng, Anyi Xu, Wenbing Jiang, Bin Wang, Peijie Sun, Peng Li, and Yonghua Huang. Simulation of sloshing and settling behavior of liquid hydrogen in an insulated tank during coastal period. *International Journal of Hydrogen Energy*, 97:117–129, 2025.

[20] Yuhao Zhu, Yu Bu, Wanli Gao, Fushou Xie, Wan Guo, and Yanzhong Li. Numerical study on thermodynamic coupling characteristics of fluid sloshing in a liquid hydrogen tank for heavy-duty trucks. *Energies*, 16(4):1851, 2023.