Numerical analysis of propellant behaviour in tanks: from small scale to industrial models

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Abstract
Propellant management is an important task in the frame of new stages development especially in the case of re-ignitable upper stages. The paper deals with the studies performed by Astrium Space Transportation dedicated to propellant behaviour in tanks. These studies are performed in the frame of the COMPERE program and internal work. First, we will present the main objectives from a system and stage development point of view, dedicated to boosted and ballistic (micro-gravity) phases. Secondly we will present work performed on characterization of sloshing frequencies of propellant tanks. The characterization of the frequencies is used in order to understand the simplified model used by GNC to identify forces and torques generated by sloshing. Finally, on a representative experiment, we have performed studies on stratification of LH2 tank to identify which models have to be used and what are the impacts on main results using CFD (Computational Fluid Dynamics) software.

1. Introduction

Sloshing of liquids in moving containers is a subject of studies and research in many engineering applications; the slosh induced loads may even be severe enough to cause structural damage The experience in the field of aircraft and launcher shows the necessity of understanding and mastering those phenomena to guarantee success of the missions as it can affect the stability of the launchers as well as the propellant feeding of the thrusters.

Because of the natural convection and aerodynamic heating, there is a large temperature difference between fluid inside a rocket tank and the surroundings. Thus propellants can be heated and flows along the sidewall of the tank toward the upper regions to the liquid–gas interface. This process generally results in the thermal stratification along the height of the tank. The thermal stratification phenomenon, especially in the cryogenic propellant tank of a launch vehicle, is an important design consideration because of its direct influence on pump cavitation, vaporization, tank pressurisation and the selection of venting devices, insulations and tank structure. Thermal stratification is affected by many factors, such as the initial liquid aspect ratio, variable liquid properties, operating pressure, thermal performance, and tank structure.

2. Sloshing

2.1 General

Sloshing is a fluidic phenomenon which is known as the formation and the propagation of waves at the free surface of a liquid in a tank partially filled. These waves motion is conditioned by external environments and particularly axial and lateral accelerations supported by the tank. Except special cases (walls especially built to absorb the waves, presence of anti-sloshing rings), the waves rebound on the walls and became stationary waves.
The sloshing phenomenon is characterised by a frequency, amplitude, sloshing mass and an inert mass (different from a fluid to another). The free surface oscillates with the natural frequency of the fluid whatever the excitation of the tank is. The undergone acceleration drives the height of the waves and so the induced loads.

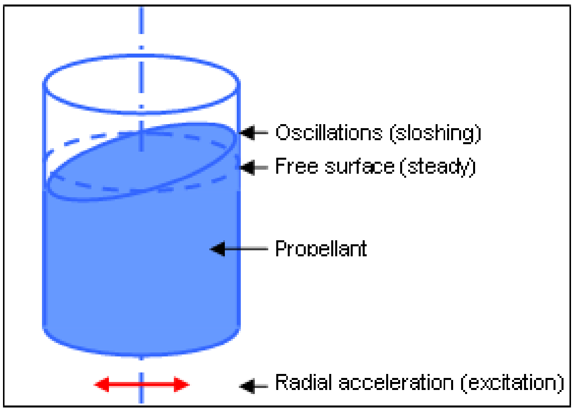

Figure 1: Schematic illustration of a slosh wave

2.2 CFD software

The sloshing effect can be simulated through several CFD (Computational Fluid Dynamics) software. Flow-3D® allows the physical modelling of the sloshing phenomena by resolution of the Navier-Stokes equations and the continuity equations of the fluid mechanics. Fluid characteristics, tank geometry and filled ratio are given as input of the calculation of the sloshing. The tank volume is divided in 3D cells (volumetric mesh); accuracy of the resulting calculation is highly depending on the shape discretization.
The forces and torques generated by the sloshing applied to the tank wall, the fluid relative velocity, temperature field, and pressure field are calculated. The position of the free surface can be deduced form the fluid ratio into the tank (0 is a gas phase and 1 is a liquid phase).
Hereafter is shown the calculation for an Ariane 5 EPC (1st stage) LOX tank shape like.

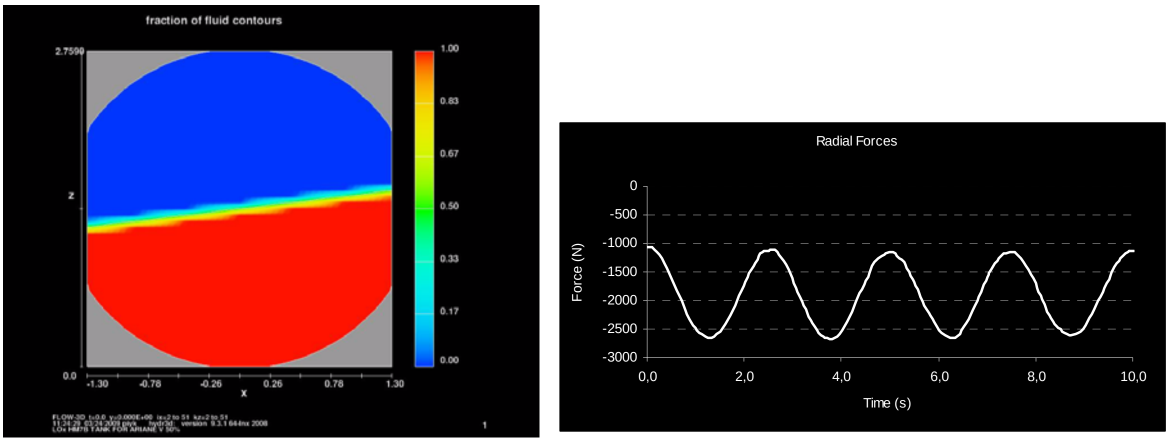

Figure 2: Sloshing calculation example with CFD software for Ariane 5 EPC (1st stage) LOX tank shape like

2.3 Equivalent mechanical model

2.3.1 Presentation

Rather than solving a detailed mathematical description of the flow, it's possible to describe sloshing as a mechanical pendulum or spring-mass model. This approach can be applied to the calculation of the sloshing loads for launcher applications, aircraft, and ships with large ballast tanks.
The lateral sloshing effect can be easily calculated by associating it to a horizontal oscillation of the liquid with a mass relative to the tank. A simplified linear spring-mass model is enough to calculate forces and torques resulting of the sloshing liquid mass inside the tank.

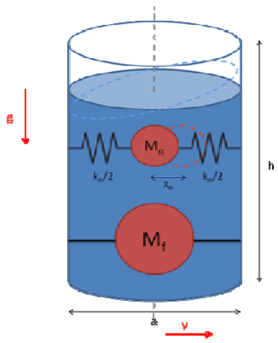

Figure 3: Schematic illustration of spring-mass model

The equations resulting from this approach are easier to use and incorporate in a control system that the equations of the fluid dynamics and are especially less expensive in time calculation and programming than CFD software. The input data for this model are the total liquid mass (Mo), the sloshing mass (Mn), the radial acceleration (γ) and the oscillation frequency (ω). A software, like ANASLOSH® can be use to calculate these input data.
After simplification of the spring-mass model, the expression of the force applied to the tank wall is,

$$F(t) = -\gamma[M_n \cos(w_n t) - M_0] \tag{1}$$

2.3.2 Results

Hereafter is shown the calculation using ANASLOSH® softawre of the force generated by sloshing inside the Ariane 5 EPC (1st stage) LOX tank for given radial and transversal accelerations.

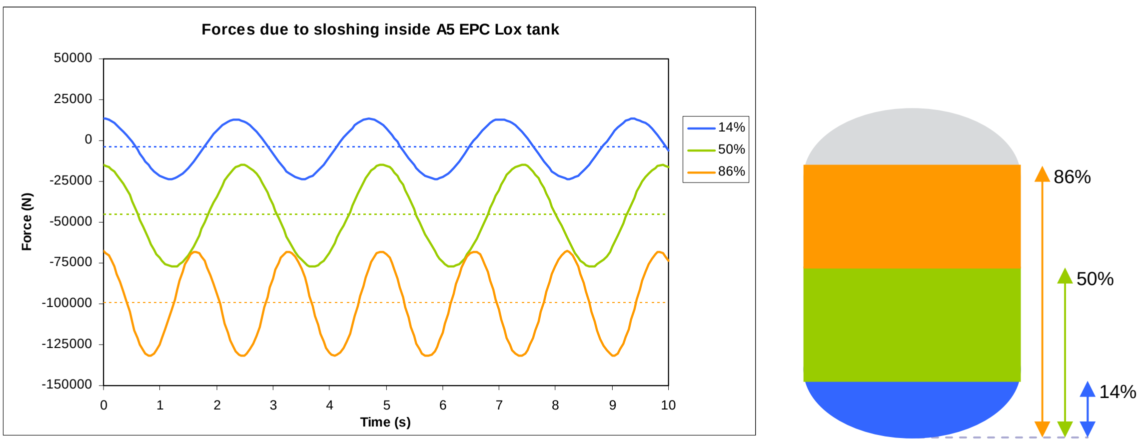

Figure 4: Analytic calculation of the forces due to sloshing for several filling ratio

The curves show the characteristics of the sloshing phenomenon (frequency, periodicity, and amplitude). The straight dot-lines show the force due to the inert mass. The curved lines show the force due to the total mass (inert mass + the sloshing mass) for each filling ratio.

2.4 Comparison of the results obtained with both approaches

Hereafter are compared the results of sloshing phenomenon for the Ariane 5 EPC (1st stage) LOX tank for different filling ratio considering the two previous models.

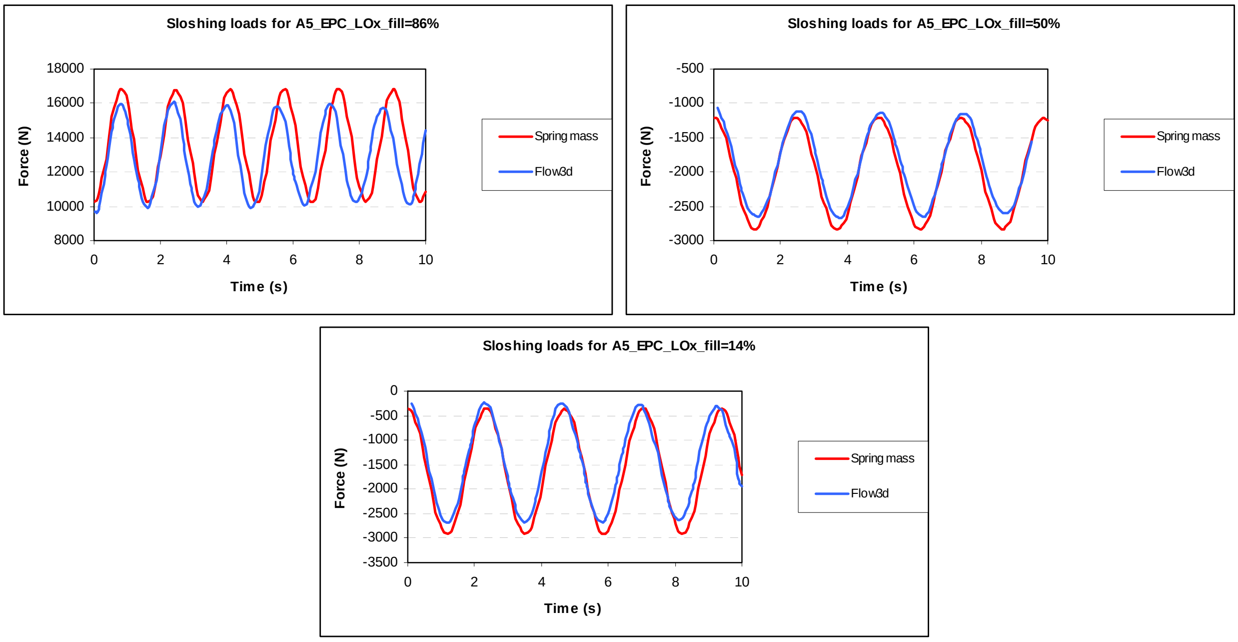

Figure 6: Comparison of sloshing loads for several filling ratio in Ariane 5 EPC LOX tank

Results show a good accuracy of the spring-mass simplified model to calculate the sloshing frequency compared to CFD calculations. This approach is thus a good alternative to perform sloshing simulations with small CPU time and resources.

3. Hydrogen tank stratification

3.1 Test case

The test case is the study of thermal stratification inside a closed LH2 tank at an initial pressure of p = 1.6 bar. Both liquid hydrogen and gaseous hydrogen phase model are used. The geometry is 2D not axysimmetric.

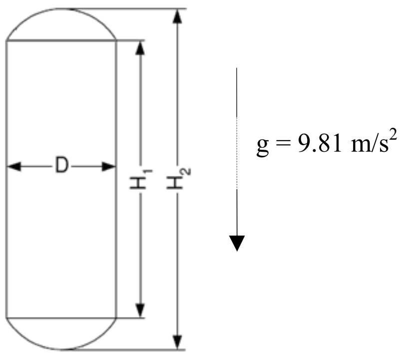

Figure 7: Tank geometry

- Tank geometry
  - height of the cylindrical part, H1 = 2.437m
  - total height, H2 = 2.827m

– diameter, D = 1.3 m

– lower dome equation –x2-z2+2.6z-0.05=0 with -0.65m ≤x≤ 0.65m and 0m ≤z≤ 0.195m

– upper dome equation –x2-z2+3.054z-0.642=0 with -0.65m ≤x≤ 0.65m and 2.632m ≤z≤ 2.827m

- Boundary conditions

Heat fluxes and temperatures are used as boundary conditions and all obstacles are considered as rigid wall. The simulation has been performed under normal gravity g = 9.81 m/s^2. The average thermal flux has been estimated from experiment.

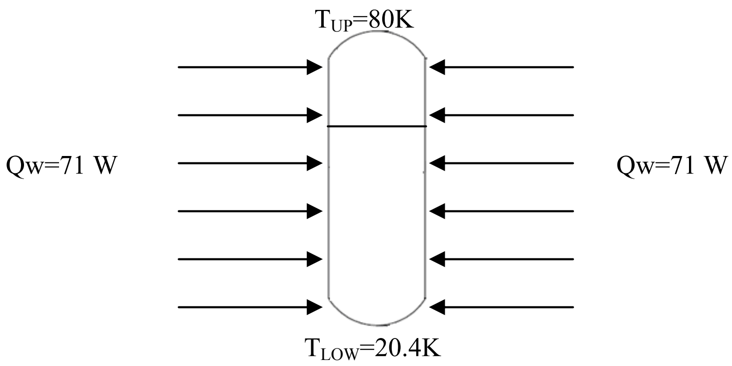

Figure 8: Boundary conditions

- Mesh

A two-dimensional cartesian mesh (x,y,z) of 75 mesh cells (x-direction), 150 mesh cells (z-direction) and 1 mesh cells (y-direction) is used.

- Initial conditions

The initial pressure is 1.6bar and initial temperatures are Tl = 20.38 K for liquid temperature and for gas temperature Tg = 8.3077× z^2+ 9.7908 × z – 13.676 with 1.52m ≤z≤ 2.82m

3.2 Results

On the hereafter figures are presented the results obtained for this test case simulation using Flow-3D® software with default parameters of phase change model and after 200s simulation regarding ullage and liquid temperature, velocity vectors.

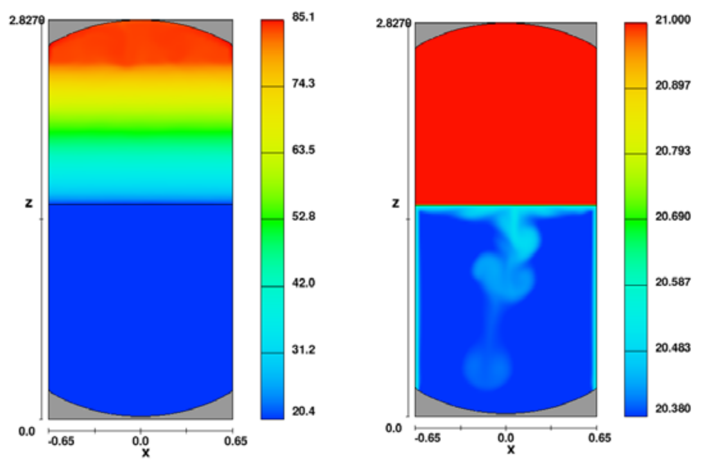

Figure 9: Ullage volume temperature and liquid contour temperature with phase change model (t=200s)

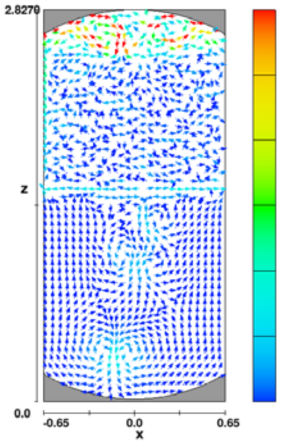

Figure 10: 2D velocity vectors with phase change model (t=200s)

A zoom on the liquid phase shows that a temperature stratification layer appears along the side walls in the liquid phase due to the heat fluxes. One can see that the phase change model impacts the temperature along the axis: natural convection phenomenon (confirmed with the velocity vectors). However considering the test case and boundaries, the temperature contour should be but is not symmetric.

3.3 Numerical solver sensibilities

- Solver

No impact of the modification of the equation solver method, the same calculation problems as initial test case occur

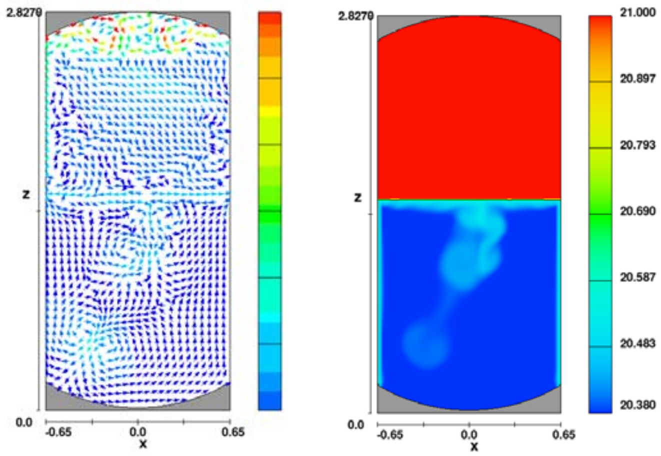

Figure 11: 2D velocity vectors and liquid temperature contour
with equation solver method changed (first to second order) t=200s

- Mesh

No impact of the modification of the number mesh cells, the same calculation problems as initial test case occur

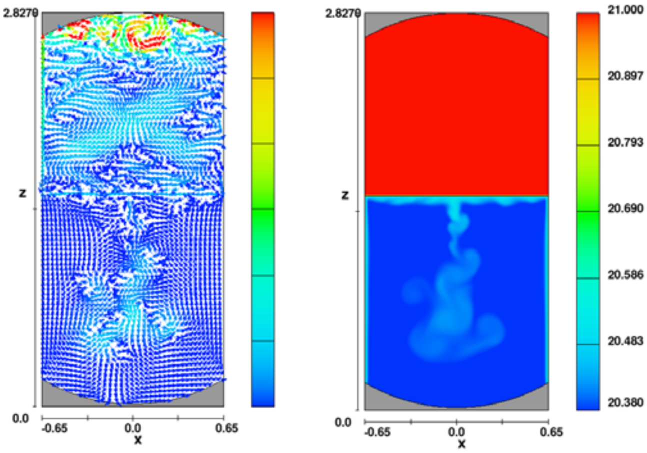

Figure 12: 2D velocity vectors/liquid temperature with greater number of mesh cells (t=200s)

- Turbulence model

Regarding the global temperature and pressure scale range, the impact of the turbulence model is negligible and same results are obtained. However a zoom on the fluid phase shows that the temperature contour is symmetric which is in accordance with the test cases and boundaries. Turbulence model has a stability effect on the calculation. Considering the velocity vectors, the gas is properly modelized with a clear natural convection at the tank top. Velocity vectors field is symmetric as it can be seen on the next figure.

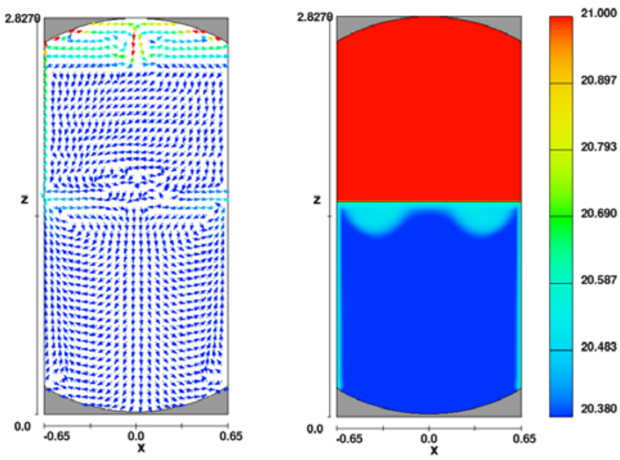

Figure 13: 2D velocity vectors/liquid temperature with modification of turbulence model (t=200s)

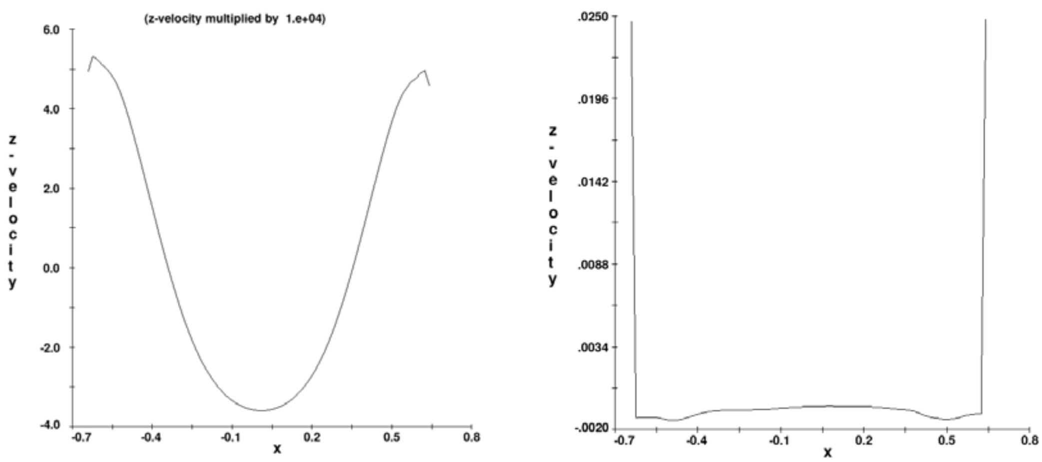

Figure 14: 1D z-velocity with turbulence model at t=200s for z=1m (liquid) and z=2m (gas)

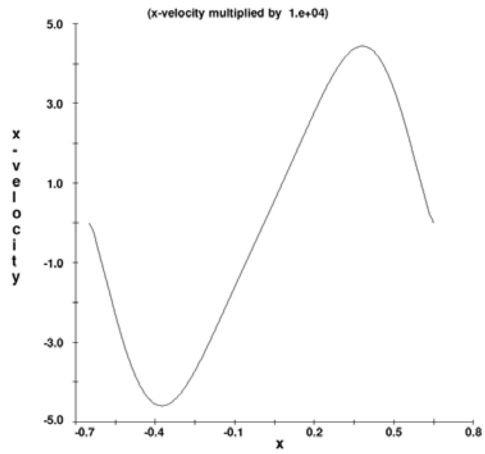

Figure 15: 1D x-velocity with turbulence model for z=1m (liquid) (t= 200s)

The turbulence and phase change model are essential to properly simulate the hydrogen tank temperature evolution with heat fluxes boundaries. This is the reference simulation case.

3.4 Accuracy of the model

Flow-3D® results are compared with experimental data from real EPC hydrogen tank studies; see [1] for presentation of the tests campaign (tank geometry, probes, installations, procedures, etc…).

Regarding global temperature field the mean slope is, for central probes, 0.17K/mn. For external probes, the mean slope is 0.46K/mn. These values have to be compared to respectively 0.11K/mn and 0.12K/mn which are the test results [1]. Thus these results are not in accordance with test results.
The results obtained in terms of pressurisation slope value are not close to experimental data (15% error). Temperature stratification layer length at interface liquid/gas isn't in accordance with results from Air Liquide (230mm w.r.t 160mm test results).

The main explanation for these discrepancies is the under estimation of evaporation. Indeed pressure in the gas phase is a key parameter for heat fluxes adjustment. Thus the next step of this study is the modification of model phase change in Flow-3D® in order to have a better accuracy.

References

[1] Barbier, F. 1996. EPC RIE, Rapport d'exploitation ballotement hydrogène. A5-RE-121-1140-CSP, Ed. 1 Rév. 1