Experimental and numerical results of sloshing with cryogenic fluids

J.Lacapere, B.Vieille** and B.Legrand***
**L'Air Liquide – Division des Techniques Avancées*
38960 Sassenage, France
***Centre National d'Etudes Spatiales – Direction des Lanceurs*
91000 Evry, France

Abstract
This document presents different sloshing experiments and computations performed with cryogenic liquids. Heat and mass transfers at the interface during sloshing phenomenon are responsible of large pressure variation in the vessel. This work helps us to understand behaviour of thermal destratification and the associated pressure decay. Comprehension of this phenomenon is crucial for future space missions with ballistic phases where free surface will not be flat. Thanks to these sloshing experiments, numerical models at the interface can be validated taking into account heat and mass transfer at the interface.

1. Introduction

To be able to anticipate and to predict temperature and pressure evolutions in a cryogenic tank of space launchers is mandatory in actual missions if we want to optimise propellant and pressurant gas masses. During propulsive phases, sloshing could occur in tanks with different pressure responses on the hydrogen and on the oxygen upper stage tanks. Future launchers with ballistic phases will also be submitted to flight phases with strong perturbations of the liquid/gas interface. Like during sloshing, these dynamic perturbations and the resulting free surface movements will be linked to thermal destratification of liquid and gas phases and thus to strong pressure variations. In order to understand these destratification phenomenons, some sloshing experiments with cryogenic fluids have been performed through the French-German COMPERE (COMPortement des ERgols en microgravité).
Destratification phenomenon and the impact on pressure evolution have been studied experimentally thanks to mixing-induced fluid destratification experiments[1]. But destratification due to sloshing and related pressure evolution has not been studied extensively even if it is an important problem in space launchers.
From a dynamic point of view, sloshing phenomenon is now quite well understood on earth or in low gravity. It has been studied extensively since the sixties[2,3]. Some anti-sloshing devices are thus well defined in tanks in order to limit pressure loads on tank walls and perturbations on the spacecraft stability[4,5,6]. But sloshing experiments performed with cryogenic fluids (and the associated pressure evolution) have not been evaluated extensively by space launcher community. M.Moran[7] performed some sloshing experiments with liquid hydrogen for National Aero-Space Plane (NASP) project and pointed out the importance of these phenomenon for future space mission with "greater bulk fluid motion" and the necessity to have "computational fluid dynamic techniques […] to accurately predict pressure and temperature conditions".
In this paper are presented different sloshing experiments performed with liquid nitrogen and liquid oxygen in order to understand thermo-hydraulic behaviour but also to have data available to perform numerical validations. Some numerical computations associated to the sloshing tests are presented in this paper.
These numerical tool could then be useful to predict complex thermo-hydraulic phenomenon occurring during future ballistic phases and associated transient phases (engine shut-down, separation phases, re-orientation phases, …).

2. Tests description

2.1 Description of the test bench

Experimental tests have been performed in 2002 with liquid nitrogen and in 2005 with liquid oxygen with the same cryostat. They have been performed in the Advanced Technical Division of Air Liquide. The cryostat used for the sloshing experiments was made of glass in order to see free surface evolution (see fig. 1). In order to limit external heat fluxes, it was made with a double wall vacuum insulated. Internal dimensions were a radius of 19 cm and a height of 80 cm.
This cryostat was instrumented with a capacitance probe in order to get the level of the free surface and with around 10 temperatures sensors in order to get thermal stratification in the liquid and in the vapor. Two pressure sensors were also added in the cryostat at the bottom and at the top of the cryostat in order to get pressure evolution during sloshing.
This cryostat and this internal equipment were also used for depressurization experiments performed also in the frame of COMPERE program in 2002.
For the sloshing experiments, the cryostat was located on a moving table in order to be able to apply sinus lateral acceleration with a specific amplitude and frequency.
The cryostat was also connected to external pressurization systems : either vapour pressurization (nitrogen and oxygen for the tests performed respectively in 2002 with liquid nitrogen and in 2005 with liquid oxygen), either helium pressurization which is considered as a non-condensable gas widely used in cryogenic propulsion.
Before producing sloshing thanks to the moving table, the cryostat is filled with cryogenic liquid and pressurized either by external gas (vapour or non-condensable gas), either through self-pressurization. The cryostat is made of glass and thermal heat fluxes are important enough to create free convection and natural stratification in the liquid and gas phases.

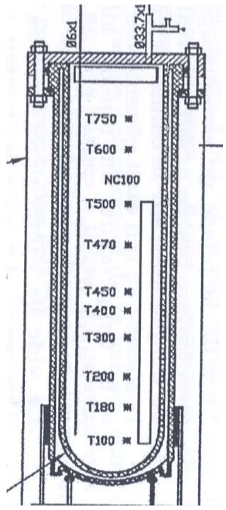

Figure 1 : Representation of the cryostat with the double wall vacuum and internal temperature sensors

2.2 Test procedure

The cryostat is opened at atmospheric pressure and is filled at the desired level (around 55 % of the total volume). When the pressure in the cryostat is stabilized, the cryostat is closed and pressurized up to the desired value (around 2.5 bar). When the right pressure value is reached, shaking is initiated at the preset frequency and the amplitude is increased to the desired value (within the first second).
Shaking is maintained the time needed to get a stable pressure. This stabilisation is achieved within the first hundred seconds.

Thus 2 different stratifications are created thanks to 2 different pressurizations, applied before producing sloshing :

- Vapour pressurization (either Nitrogen – GN2, or Oxygen – GOx), which creates a very strong thermal gradient within a very small liquid layer at the interface. Pressurization up to 2.5 bar was performed within 100 s.

- Helium pressurization (GHe), which creates a small thermal gradient within a very small liquid layer. Pressurization up to 2.5 bar was performed in this case within 50 s.

The sloshing tests with liquid oxygen have been performed 3 years after the tests with liquid nitrogen. Thus, the apparatus inside the tank (temperature sensors, capacitance probes, …) and outside the tank (pressurization line, helium capacity, sonic orifice, …) were not exactly the same in the two experiments.

2.3 Test parameters

2 different cryogenic fluids have been tested : Liquid Nitrogen (LN2) and Liquid Oxygen (LOX)
2 different pressurizations => 2 different thermal stratifications, 2 different ullage compositions
Different shaking parameters leading to strong or smooth free surface deformations

In this document, we will focus only on sloshing close to the first frequency of the cryostat and with vapor pressurization. In fact, we will focus only on the destratification phenomenon of the previously stratified liquid layer and the associated pressure decrease.
Sloshing is performed close to the first frequency, which is around 2.1 Hz for this cryostat.
Shaking is a sinus excitation with 3 mm amplitude and 2.1 Hz frequency.
Two sloshing experiments are thus presented in this document with only one excitation (frequency 2.1 Hz and amplitude 3 mm) : One with LN2 pressurized up to 2.5 bar with GN2 and the other with LOX pressurized up to 2.5 bar with GOx.

3 Numerical approach

3.1 Description of the numerical models

The Fluent CFD code is used for these computations with the Volume Of Fluid (VOF) model to take into account sloshing. The “geo-reconstructor” scheme is used in order to be precise on the free surface behavior.
Surface tension effects are not present in these computations, but these effects could be taken into account when needed (when Bond number is less than 10 for example).
Using the VOF model, Fluent code is able to solve energy equations with average properties values at the interface. Thus, a modification is made to the fluent code through User’s Defined Functions (UDF) in order to take into account mass transfer between liquid and gas phases. In our sloshing case presented in this document, condensation phenomenon at the interface occurring during destratification is the major phenomenon to explain ullage pressure evolution and such an extension to the Fluent code is mandatory to compute cryogenic sloshing.
Liquid phase is supposed to be a dilatable liquid : density is written as a function of temperature. Gas phase is supposed to follow the ideal gas law : density is written as a function of temperature and pressure.
Second order discretization is used for momentum and energy equations.
The numerical models are 3D, but with symmetry plane which is coherent with the sloshing axis.
To impose sloshing, sources terms (forces) are added thanks to UDF in the momentum equations integrated from displacement imposed by the moving table.

3.2 Mesh and initial conditions

The cryostat is modelled without internal equipment and without the solid walls.
A very simple model is used consisting in half a cylinder (only half of the geometry is modelled).
The mesh contains non-uniform hexahedral cells with refined cells close to the interface and more coarse cells at the bottom and at the top of the domain (see fig. 2). Cells at the initial interface have a size around 3 mm and cells at the extremity have a size around 1 cm.

Figure 2 : Mesh of half of the cryostat (~ 20 000 hexahedral cells)

Even if free convection is present in the cryostat, it is not modelled in our computation in so far as the pressure impact is considered as negligible during the hundred of seconds of sloshing. Thus, walls are considered as adiabatic.

The computations begin at the beginning of the shaking perturbations. Previous pressurization is not modelled but the impact of this pressurization is taken into account through initial thermal stratification (from tests data)

Initial thermal stratification and initial pressure in the tank before sloshing are imposed in the computations by interpolating values obtained by experimental tests after pressurization (just before sloshing).

For example, see fig. 3 to have the initial thermal stratification corresponding respectively to liquid nitrogen pressurized with nitrogen vapor (LN2/GN2) up to 2.5 bar and to liquid oxygen pressurized with oxygen vapor (LOX/Gox) up to 2.5 bar.

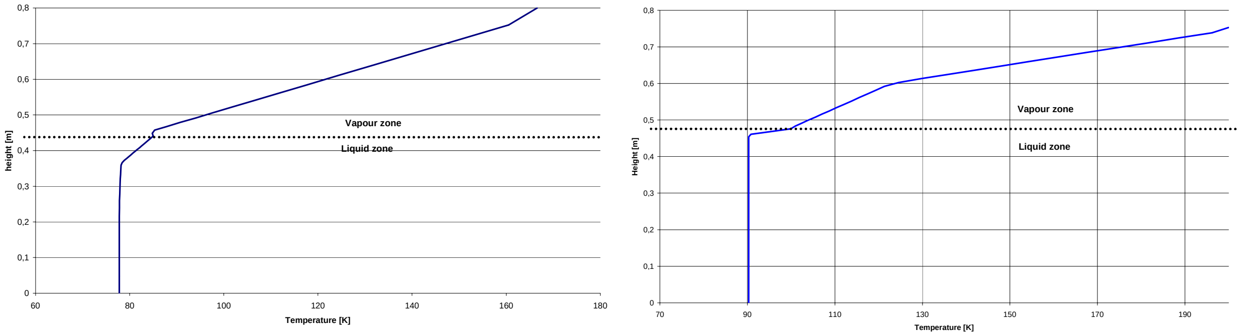

Figure 3 : initial stratification in the cryostat just before sloshing for LN2 pressurized with GN2 on the left and LOX pressurized with GOX on the right

The thermal stratifications have a very strong gradient near the free surface : large température variation in a very thin layer. Thermal stratification of LOX is for example very strong because of the very rapid pressurization phase (compared to the LN2 case).
The following figure (fig. 4) is showing for example the corresponding initial stratification imposed in numerical computations before the beginning of sloshing

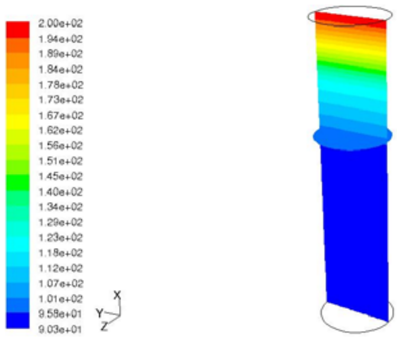

Figure 4 : Visual representation (on the symetry plane and on the free surface) of the initial thermal stratification on the cryostat (LOX/GOX) before sloshing

In the following figure 5, a different range is used in order to see thermal gradient in the liquid phase near the free surface (LOX/GOX)

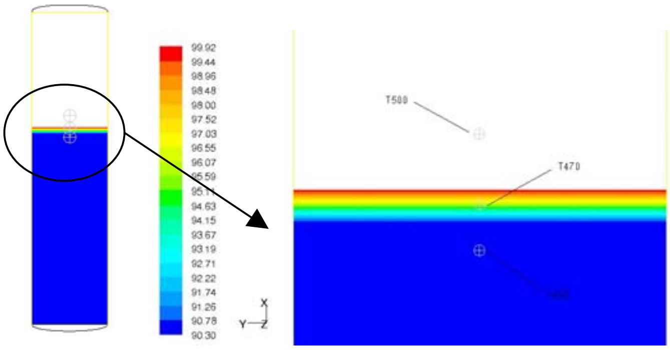

Figure 5 : Visual representation of the thermal stratification on the liquid only in the cryostat (LOX/GOX) with position of temperature sensors

4. Results and discussion

Sloshing occurs in the stable region close to the first frequency of the cryostat leading to large amplitude waves but not to breaking waves neither to droplets ejections (see fig. 6).

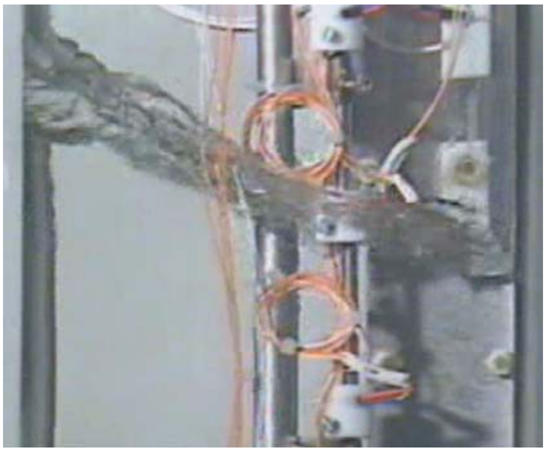

Figure 6 : Visualisation of experimental free surface deformation during sloshing experiment (LN2)

4.1 Thermal destratification

Destratification phenomenon is clearly visible during sloshing tests thanks to the different temperature sensors in the liquid phase and more precisely near the free surface (see fig. 7 for temperature evolutions during LOX/GOX sloshing).

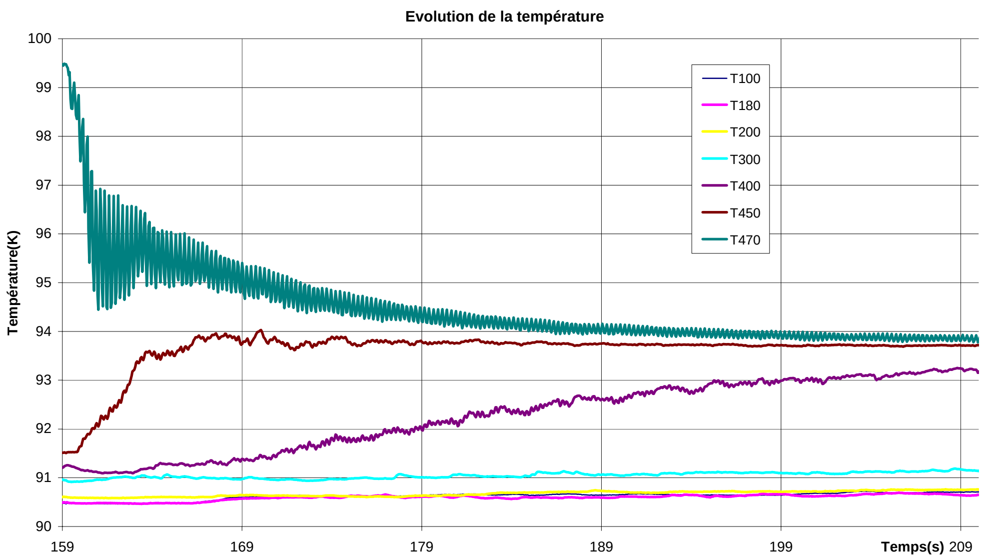

Figure 7 : Evolution of temperature in the liquid phase during sloshing experiment (LOX/GOX)

Shaking of the cryostat begins at time 159 s
The different temperature sensors are located at 100, 180, 200, 300, 400, 450 and 470 mm from the bottom of the cryostat. Initial liquid level is located at 472 mm (just above the temperature sensor T470).
The initial thermal stratification is destroyed within the first 50 seconds of sloshing. The temperature gradient becomes very smooth and the liquid layer becomes thick. The temperature near the free surface is no more stratified but homogeneous.

Destratification phenomenon during sloshing is also clearly visible in numerical computations (see fig.8). Subcooled liquid is going up to the interface and is able to condensate a large quantity of vapour leading to a large pressure decrease in the cryostat.

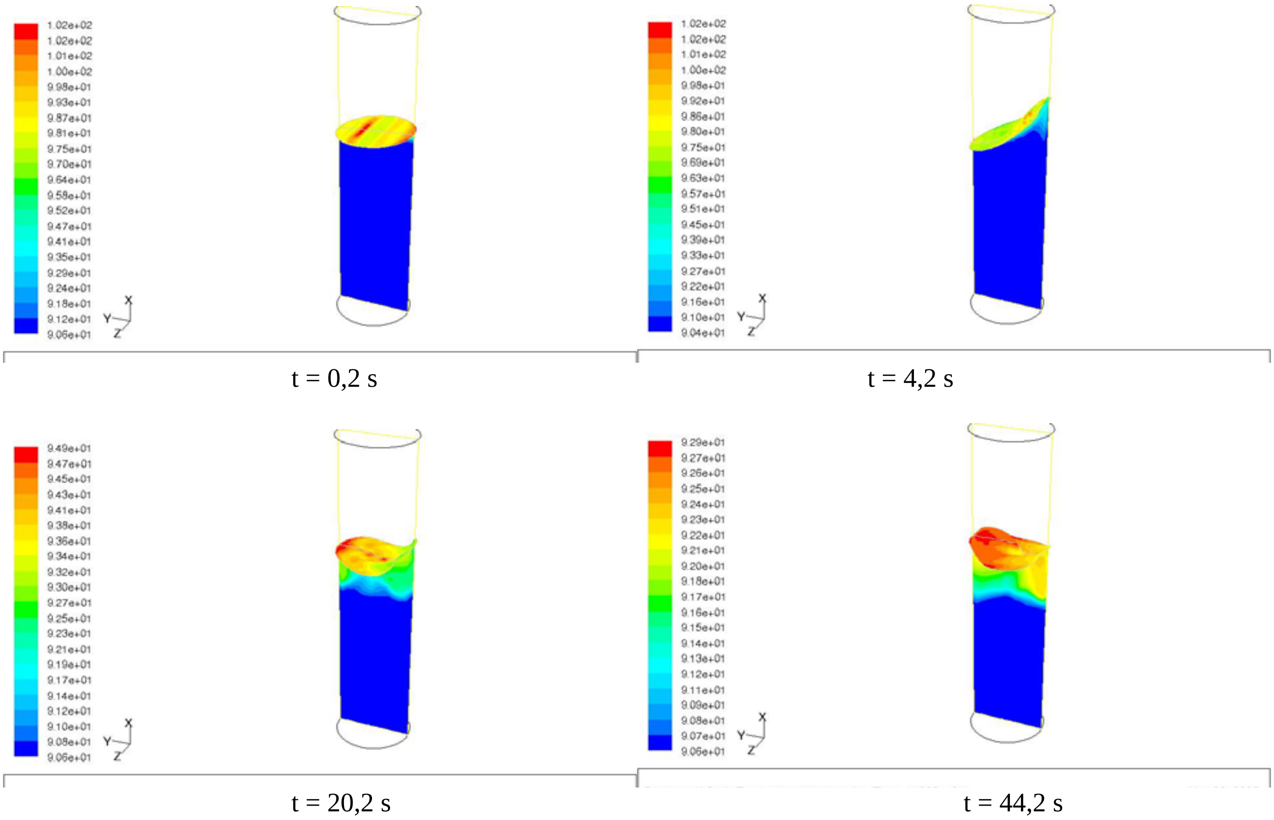

Figure 8 : Evolution in time of the thermal stratification in the liquid phase – Visualisation in the symmetry plane and on the free surface – CFD Results (LOX/GOX)

At the end of the sloshing phase, temperature distribution in the liquid is very different (see fig. 9):

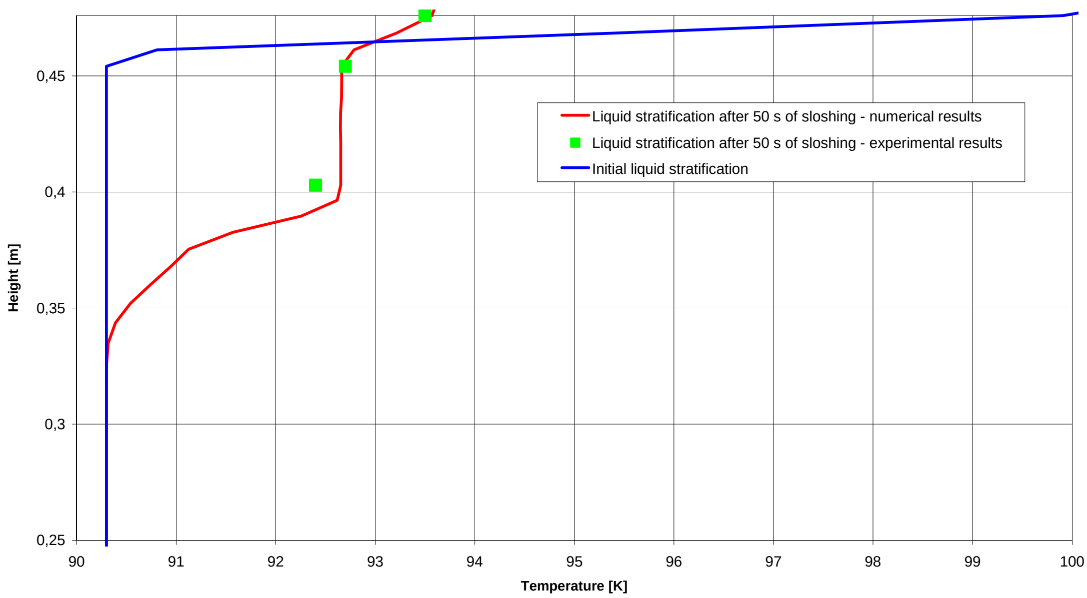

Figure 9 : Thermal stratification in the liquid phase (before and after 50 s of sloshing LOX/GOX)
The upper height limit corresponds to the position of the initial free surface

At the end of sloshing, temperature near the free surface (liquid phase) is more homogeneous. The free surface temperature has decreased.
Thermal destratifications are in good agreement in the experimental and the numerical results. The capacity to condensate vapour phase is thus well computed by the numerical model.

4.2 Pressure evolution

Figure 10 shows pressure evolutions obtained in experimental tests and in numerical tests. 2 different sloshing experiments are compared with 2 different fluids (LN2 pressurized with GN2 and LOX pressurized with GOX) but with the same lateral excitation : frequency 2.1 Hz and amplitude 3 mm

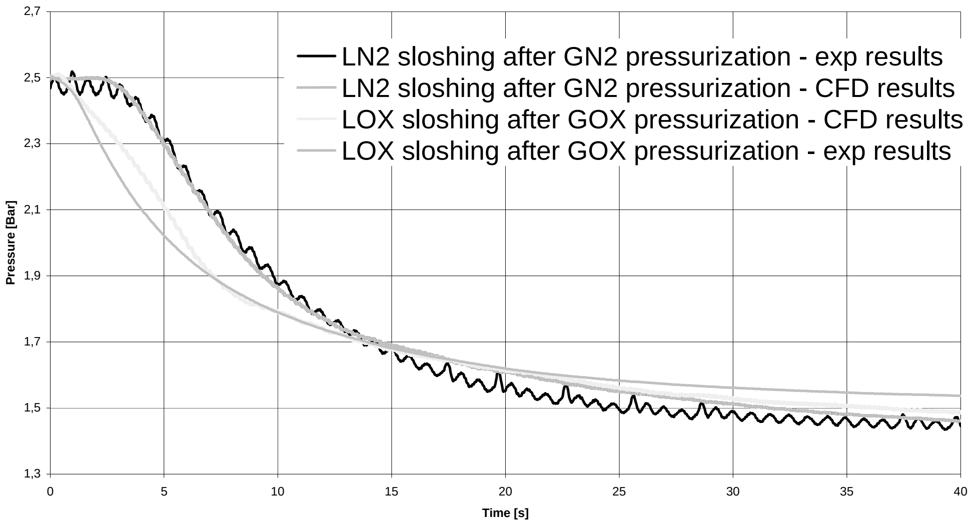

Figure 10 : Comparison of pressure evolution in the cryostat between experimental results and numerical results for LN2/GN2 sloshing and LOX/GOX sloshing

The evolutions of pressure in the experiments and in the numerical computations are in very good agreement for liquid nitrogen experiment and liquid oxygen experiment.
Pressure evolution is very important during the first fifteen seconds of sloshing (from 2.5 bar down to 1,7 bar). Pressure stabilizes then around 1.5 bar.
The pressure decay is more important in the very first seconds of sloshing for the LOX tank initially pressurized with GOX because of the initial stratification in the liquid. This initial stratification in LOX was strong (compared to initial stratification in LN2) ; see fig. 3 and 5. This stronger initial stratification in LOX has been created by a faster pressurization phase.
These pressure evolutions are very important and are not representatives of pressure decay occurring during thrust phases of upper stage launchers (initial stratifications are not so strong and waves amplitude is not so important).

5. Conclusion

The destratification process in the liquid phase is represented in this paper thanks to the comparison of experimental sloshing tests with cryogenic fluids and numerical results. The destratification process is responsible of large pressure decrease in the cryostat.
This pressure evolution and the thermal evolution in the fluids are well computed by the numerical model.
This numerical model could also be used in the future to compute pressure and temperature evolution occurring in future upper stage cryogenic tanks submitted to different external perturbations (engine shut-down, separation phase, re-oriention before re-ignition, …).

References

[1] Abramson, H.N. The dynamic behaviour of liquids in moving containers. NASA SP 106, 1966
[2] Dodge, F.T. Analysis of small amplitude low gravity sloshing in axisymmetric tanks. Microgravity science and technology, vol 4, pages 228-234, December 1991
[3] Stephen, D.G. Liquid-propellant dynamics and suppression, NASA Space Shuttle Technol. Conf. page 139-174
[4] Kannapel, M.D. Liquid oxygen sloshing in space shuttle external tank. AIAA 87-2019
[5] Lung, R.J. Slosh wave excitation and stability of spacecraft fluid systems. TABES Paper 90-1810
[6] Moran, M.E., Mc Nelis, N.B., Kudlac, M.T., Haderbusch, M.S., Satornino, G.A., Experimental results of hydrogen slosh in a 62 Cubic Foot (1750 Liter) Tank. AIAA 94-3259