PRESSURIZATION MODELING FOR LAUNCHER TANKS

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ABSTRACT

For the cryogenic tanks, the modeling of the fluid behavior may be oriented towards bulk and ullage modeling. The first one is performed in order to identify thermal stratification which may generate residuals, sloshing for pressure evolution ("Creux"), reorientaiton during balistic phases and other phenomenon like boiling, recondensation...

The second one is performed in order to estimate pressurization needs and pressure range definition. This allows identifying the mass needed the pressure evolution definition versus time and then gives the needs to engine designer, in boosted phases as well as during balistic phase propellant management.

In order to consolidate the pressurization budget for boosted phases, some methods have been reviewed and applied to known LOX tank. The results of these methods of different levels used by EADS Airbus Defence and Space will be presented and compared. The roughest one based on empirical method, more advanced method based on 1D simulation will be also presented applied on a LOX-tank with comparison with real data. Finally, we present CFD approach based on FLOW3D analysis and compared to previous methods and real values from flight results.

In conclusion, we will discuss on applicability of each kind of methods depending on project status, thanks to results presented.

INTRODUCTION

During the operation of a liquid propellant stage, the ullage pressure may be maintained between a given range of pressure. Pressure levels are determined for one part, by the engine and feed systems requirements, and for the other part, by mechanical requirements. Several fluids may be used for pressurization like Helium, gaseous Hydrogen and gaseous Oxygen. Pressure Control may be performed also thanks to several methods by throttling, on-off device or sonic flow orifice. As the pressurization system mass and cost may represent a non negligible part for the vehicle, modeling and estimate of the pressurant mass (and the associated system) is often critical during the development phases. Then it is mandatory to be able to obtain the good order of magnitude for this system.

PRESSURANT MASS COMPUTATIONS

Several methods have been used during the space age in order to predict the pressurant mass for a rocket stage. The oldest and simplest one is to compute thanks to the perfect gas law the volumetric mass and multiplying by the ullage volume to obtain the mass. An improved method has been proposed by Epstein [1] in the sixties taking into account several parameters like kind of propellant, tank material…based on previous methods coupled with empirical correlations. Those methods remain based on 0D approach and on empirical. The main drawback is the choice of the average ullage temperature, which drives the mass computed. In Airbus Defense and Space, we can use other means relying on 1D tools and CFD codes. Mono-dimensional computations are based on EcosimPro platform. Several CFD tools may be used, but we rely on Flow3D® which is intensively used for propellant management purposes, especially sloshing. As always, the challenge is to validate this kind of tools and well defined the methodology to be applied. We will present here applications of out tools to Ariane 5 first stage LOX tank.

ACRONYMS

EAP	:	Etage d'accélération à Poudre
EPC	:	Etage Principal Cryotechnique
ESC-A	:	Etage Supérieur Cryotechnique - A
SSHel	:	Sous Système Hélium Liquide
EPS	:	Etage à Propergols Stockables
EVi	:	Electro valve i
M1	:	Mesh 1 : 15 x 160
M2	:	Mesh 2 (refined) : 30 x 290
P	:	Pressure
P_{max}	:	Pressure Upper Value
P_{min}	:	Pressure Lower Value
t_{end}	:	Flight Final Time
T_{max}	:	Temperature Upper Value
T_{min}	:	Temperature Lower Value

ARIANE 5 LOX TANK PRESSURIZATION SYSTEM

Ariane 5 launcher is a two-stage vehicle with two solid propellant boosters (EAPs) used during the beginning of the flight and which delivers high-trust for take-off and acceleration level at “low” altitudes. Both stages are cryogenic one: EPC and ESC-A, both with LOX/LH2 propellants respectively with Vulcain 2 and HM-7B engines.

The main stage contains around 170 metric tons of propellant in a tandem tank configuration with common bulkhead. The oxygen tank of the main stage is pressurized by Helium gas stored in liquid state in SSHel. The helium is then heated and injected into the tank through flow control valves and calibrated orifices. The schematic of the system is presented by the following figure, including the common bulkhead tanks and the liquid oxygen pressurization lines and equipments.

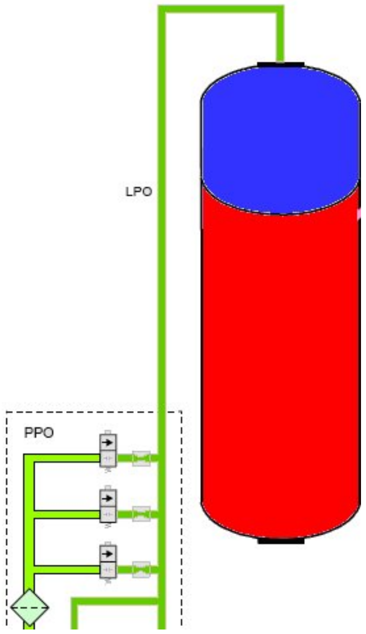

Figure 1 : EPC Pressurization system

The tank pressure is regulated by a pressurization plate which includes three orifices and three electrovalves driven by the onboard computer. The system has been developed for the need of Hermes shuttle, which was planned to be used by human beings, and then safety issues induced by human flight have been adressed. One electro valve is permanently in open position delivering constant flow in the tank. The second is activated time to time to maintain the pressure between lower and upper limit of the pressure range. The third valve is a redundant one, covering the failure of the previous valves. The device is shown hereafter.

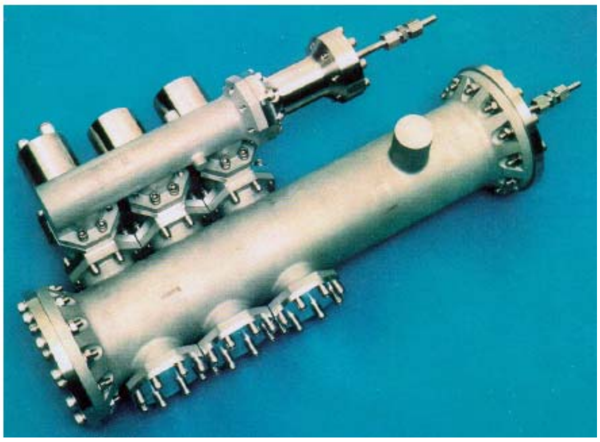

Figure 2 : LOX Pressurization Plate

Thanks to flight measurements, we dispose of pressure in the tanks and Helium injection temperature. By post flight analysis, we dispose of other parameters, by consequence, for instance, Helium mass consumption is well known. Then it allows us to use these data to validate our tools applied to pressurization analysis.

FUNCTIONAL MODELS

The functional modeling of liquid propelled stage has been started in early 1990. Based on Fortran language, some dedicated tools have been developed and validated in Les Mureaux, mainly oriented on Ariane 5 stages: EPC and EPS for instance. These tools have been written in Fortran, to take benefit of the wide panel of tools existing at this time in the propulsion engineering department. After, in order to obtain more versatile tools able to model quickly the miscellaneous architectures and technologies we may encounter on launchers, the decision has been taken to switch to a tool more interactive compared to Fortran “frozen” tools, which are not so modular and needs sometimes large change when architectures are evoluting. Several tools have been used and tested between teams inside Airbus dedicated to launcher propulsion. We decide to rely on Ecosim Platform, which is a platform dedicated to 1D simulations.

ECOSIMPRO TOOL

The Ecosim Pro tool is suitable for modeling systems which may be simplified to 1D system. It is a non-causal tool: modeling does not require writing the equations with the order are in which the variables are calculated. The tool includes dedicated libraries dealing with command boxes, fluids, rocket engine and stage components, network elements, which permits to model a wide range of problems for liquid propulsion purposes. It is developed by Empresarios Agrupados S.A. In order to model the pressurization loop, we decide to use the unsteady library named ESPSS, which has the advantage of having pre-defined components adapted to the pressurization modeling.

The flow synoptic presented here, has been represented as shown in the following figure with the valves EV1, EV2 and EV3 and the LOX tanks. Boundary conditions have been also added for thermal fluxes, Helium injection conditions and LOX tank draining. The data used have been set from the flight V190/L548.

MODEL

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- The geometry of the Lox tank : radius, bulkhead size and shape,
- LOX loaded mass,
- Pressure range aimed (Pmin and Pmax versus time)
- LOX mass flowrate versus time,
- Initial conditions: Ullage pressure and Temperature, Propellant temperature.

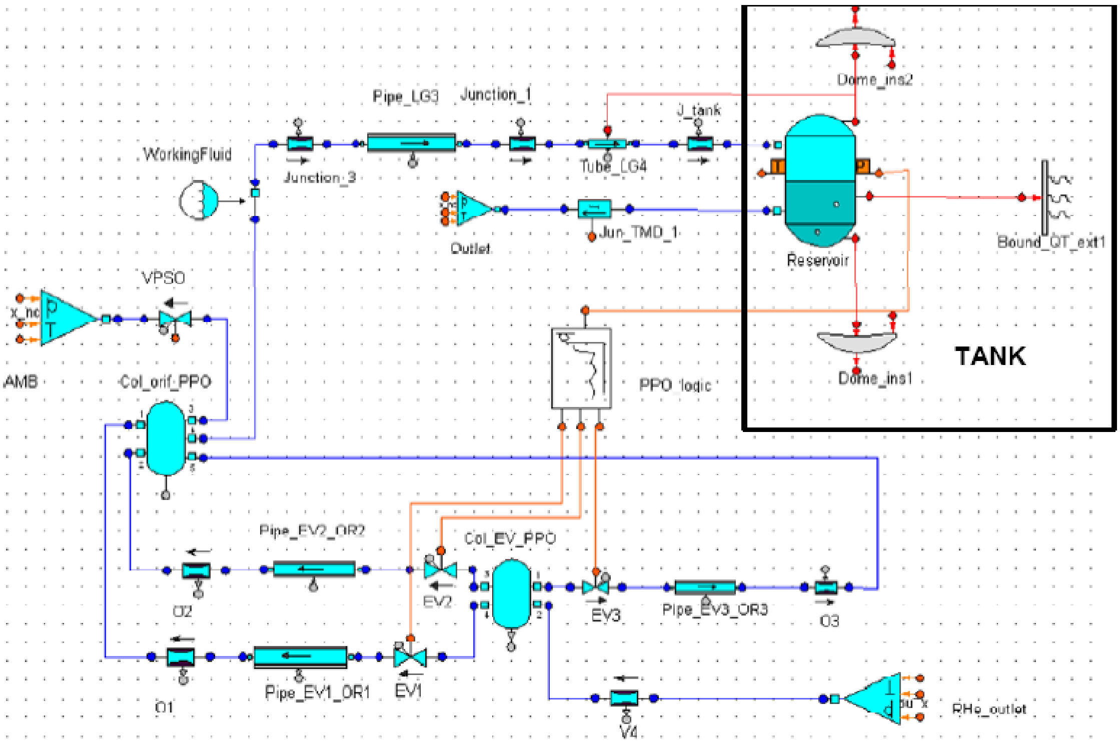


Figure 2 : Flow schematics of LOX tank pressurization

In the gas phase, two components are considered: the propellant vapor and a non condensable gas (helium in this case) which behaves as an ideal gas. Mass, momentum and energy conservations are applied for each node of the liquid and gas volume. Conductive transfer in wall nodes is applied to calculate the wall temperature. The thermal exchange between fluid and wall is calculated thanks to a heat exchange coefficient using “standard”correlations.

The mass and heat transfers are calculated at the liquid/gas interface to assess the vaporization or condensation rate. It is possible to apply a coefficient (“turbulent factor”) in the calculation of transfer coefficient to take into account possible interface movement. The energy balance approach was applied for the reference case.

The tank is then represented by successive layers representing both gaseous (for the ullage) and liquid propellant (for the bulk) as represented after:

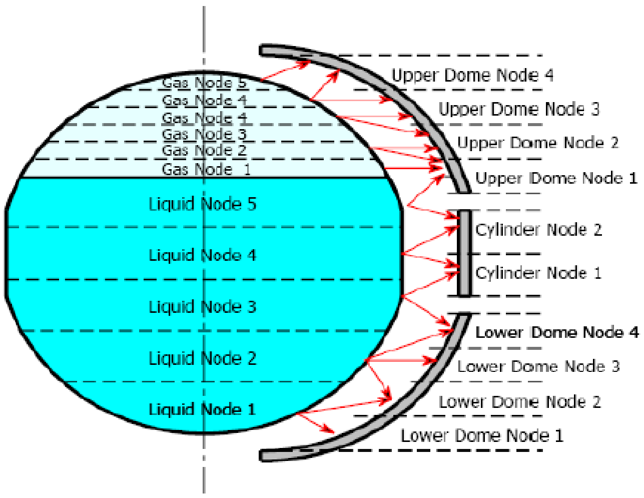


Figure 3 : Tank model for Ecosim Pro Tool

The main criteria of comparison will be the pressurant mass as it is known during the flight and well estimated. Some uncertainties remain which have been covered by parametric studies.

The model is build with 30 nodes for the ullage volume and 5 for the bulk in our main computation, in order to focus on the ullage region and have a good meshing at the ende of computation, when this volume growths and becomes close to the overlall tank volume. Final computation takes roughly one hour (real time).

The flight has been simulated from ignition of engine until 500 s. The simulation is performed with the constraint to respect the pressure range. It means that the comparison has to be performed on the evolution of pressure versus time and on the pressurant mass compared to flight analysis. The comparisons have been done on pressure level and evolution versus time as well as on pressurant mass.

RESULTS

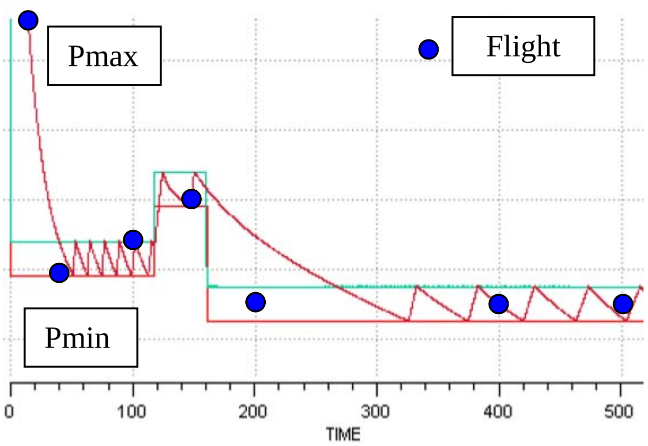


Figure 4 : Lox Tank Pressure versus time

One can see on the previous curve the comparison between simulation and flight. The level and the pressure range are well respected. Main discrepancies is linked to the expansion which have a longer duration compared to the flight especially the second one. It may be linked to the value of specific heat ratio, which may be not comparable with the real one. The final results in term of Helium mass are presented hereafter:

Parameter	Flight	Ecosim
Hélium Mass	Ref	-15%
Diffuser Temperature	Ref	0%
Top of cylinder Temperature	Ref	+9.8%

Figure 5 : Mass and Temperatures Results

The results obtained are quite coherent; temperature is overestimated leading to decrease of the mass needed in order to pressurize the tank. Some parametric studies have been performed on main parameters (heat exchange, fluxes, nodes number…) None of them give strong discrepancies, especially nodes number increase in the fluid has no influence and in the walls increase the pressurant by one percent.

As written before, this kind of tools allows modeling 1D geometry or equivalent. In some case, it becomes mandatory to model the tanks taken into account 2D and 3D effects.

Then we decide to compute same test case with a CFD tool used in Airbus Defence and Space for sloshing and propellant management in propellant tanks: Flow3D®.

FLOW3D® MODEL

Flow3D® is a CFD tool dedicated to sloshing and propellant behavior developed by Flow Science and widely used for all the topics related to sloshing and fluid behavior phenomenon. It is widely used in Airbus Defence and Space for a large range of topics, including pure sloshing, control issues and tanks thermal models [6], e.g. for A5ME upper stage. It used Volume of Fluid Method for the free surface tracking and solves the Navier-Stokes equations. A lot of options are available due to the wide range of applications covered by the tool, not only in the space field. Application to pressurization has been performed in the past on a spherical tank containing slush LH2 and with GH2 injection on relatively short time [5].So we consider that we may check the capability of the tool to deal with this kind of process.

MODEL

Flow3D® is a three-dimensional tool, with no two-dimensional option. For modeling the EPC Liquid Oxygen tank, we make some assumptions in order to simplify the geometry and then perform a first evaluation of the tool applied to the pressurization modeling. The advantage of using LOX tank as a reference case is that we limit the phase change influence we may have by dealing LH2 tank pressurized by propellant vapor.

Main assumptions are given here:

- The computation domain is an angular region of 30° given wall temperature in order to be close to an axisymmetrical computation
- The wall is not taken into account in the computation domain
- The equipments of the tank are not represented: internal feeding line, Antisloshing devices, antivortex, and diffuser. In order to avoid interaction of Helium flow with free surface, especially at the beginning of flight simulation, a thin plate has been defined to diffuse the pressurant flow along the walls,
- The initial temperature is supposed to be linear from the measured value in the top of the tank to the bulk value.
- The pressurant mass flowrate is put as boundary condition at the top of the tank. The values (temperature, mass flow values...) are directly derived from flight analysis data.
- The engine mass flowrate is taken constant for all the flight phase except for the ground phase for which we take into account thrust build-up. The engine shutdown has not been computed.
- Only longitudinal acceleration is taken into account (nor lateral forces nor angular motion)
- The computation does not consider turbulent flows; the flowfield is solved with the laminar hypothesis.

The mesh cells number along x axis and z axis are respectively equal to 15 and 160 which corresponds to 2400 grid cells. An influence of the mesh size as been performed by refining the mesh (roughly multiplying by four the cells number): 30 x 290 grid cells.

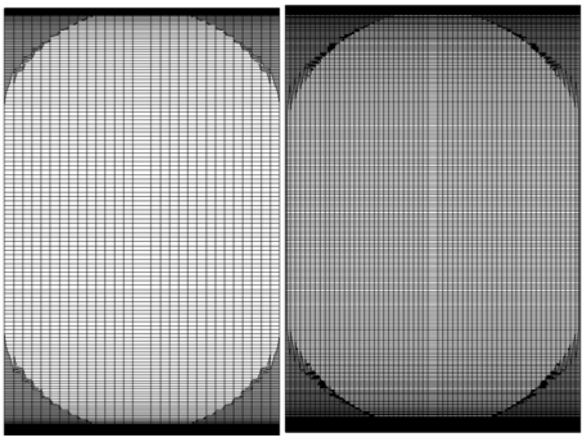


Figure 6 : Lox Tank Mesh 1 and Mesh 2

RESULTS

We present here the evolution of pressure obtained for refined mesh compared to flight values. Compared to the EcosimPro simulation, the Helium mass is correct (as given and checked by inlet conditions) and then the differences will be seen on the pressure curve.

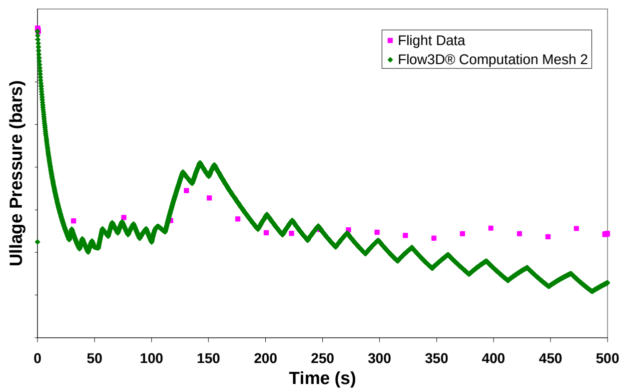


Figure 7:
Pressure Evolution versus time for Mesh 2

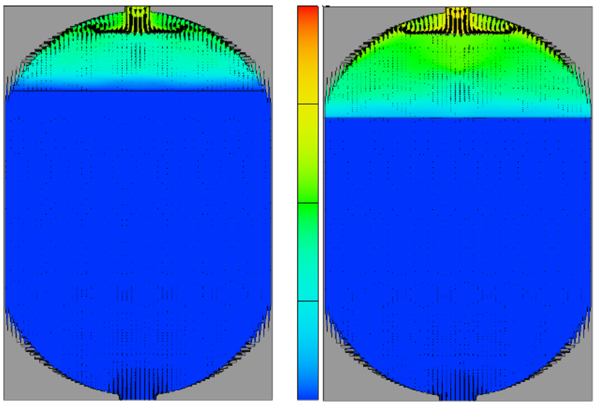
One can see that evolution is rather good: strong expansion at the beginning (time less than 30 s) with coherent values in time and pressure. Between 100 and 250 seconds, experimental and computed values are close together. After this time, we have a constant decrease for computed values, leading to the maximum difference at the end of simulation. The differences are given for discrete times of the simulation.

Time (s)	Flight	Flow3D® M2
40	Reference Values	-3.9%
100		-5.9%
150		+4.2%
200		+3.8%
300		-2.1%
400		-9.3%
500		-11.6%
Average	-4%	

Figure 8:
Experimental versus Computed Pressure Values

Even if last values present a accuracy around 10%, it is encouraging that with relatively simplified assumptions, shape of the pressure is good, and average difference lower than 5%.

As pressures present some differences, we have a look on the temperature values. Of course, we have no detailed charts of temperature inside tanks, but have a look on the ullage stratification allows us to compare to less sophisticated methods. Hereafter the evolutions of the temperatures in tank are presented at miscellaneous times of flight.



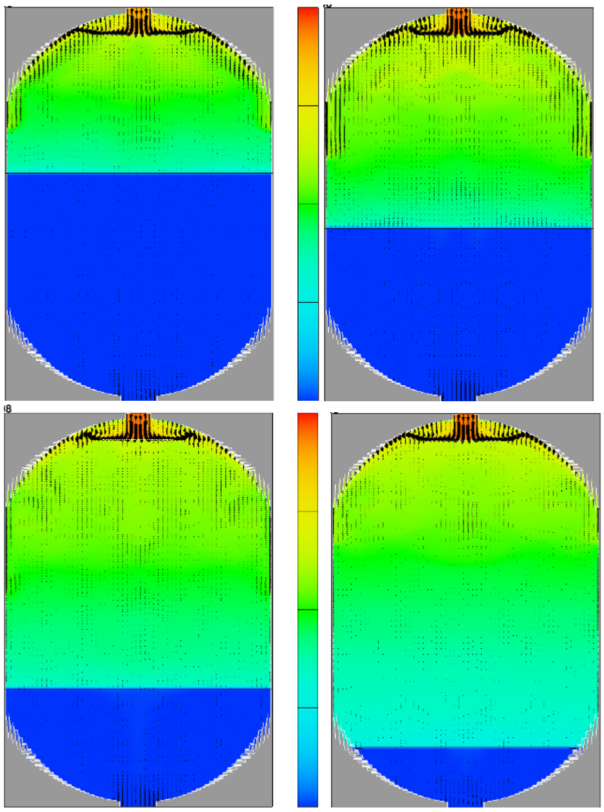


Figure 9 : Lox Tank Temperature Charts Evolution versus time Mesh 2 (50,100,200,300,400 and 500 s)

Time	Flight	Flow3D® M2
T $_{ullage\ upper}$ (t=tend)	Reference values	0%
T $_{ullage\ cylinder}$ (t=250 s)		-12.5%
T $_{ullage\ cylinder}$ (t=tend)		-14.6%

Figure 10 :
Experimental/Computed Temperature Values

First it can be seen that, we obtained a stratification of the ullage as seen in the 1D computation. The discrepancies exist a little bit along the wall in the upper part, but with only longitudinal accelration, flow is quasi 1D. The differences are larger compared to the results on pressure. If, the injection temperature is correct, we observe a difference of 15% on the temperature in the highest point of the cylinder part of the tanks. The reason is surely due to the wall temperature hypothesis, which "overcools" the ullage. It may also explain the pressure level decreasing along the second part of the simulation: energy dedicated to pressurizing may be drained by the wall, as we freeze the value at propellant temperature (sizing conditions).

The consequence is that an effort has to be done on the identification of thermal conditions : wall temperature, heat fluxes characterization….

MESH INFLUENCE ANALYSIS

Several parametric studies have been performed in order to check the impact on the results in term of pressure evolution versus time. The main topic, which will be detailed here, is the mesh size. The results presented above have shown real but relatively small influence.

Time	Flow3D® P(M1)	Flow3D® P(M2)
t=40	-2.7%	Reference values
t=100	-4.4%	
t=150	-4.5%	
t=200	-6.5%	
t=300	-6.1%	
t=400	-5.6%	
t=500	-5.5%	
Average	-5.8%	

Temperature	Flow3D® M1	Flow3D® M2
$T_{\text{ullage upper}}$ (t=tend)	0%	Reference values
$T_{\text{ullage cylinder}}$ (t=250 s)	-5.7%	
$T_{\text{ullage cylinder}}$ (t=tend)	-6.1%	

Figure 11 :
Mesh influence on Pressure and Temperature

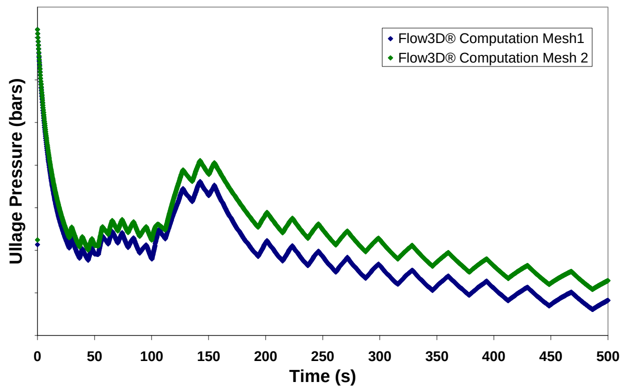


Figure 12:
Pressure Evolution versus time for both meshes

The pressure curve are fully coherent, and the evolution is exactely the same. If we compare to the previous 1D results, the main difference is on the second expansion is shorter and more coherent of flight results.

If we have a look on the influence of the mesh on the temperature and velocities flowfield one can see:

The main differences are on the ullage temperature flowfield. Stratification of the ullage is a little bit different: cold layer is larger with the refined mesh. By contrary, along the bulkhead walls, hot layer is thiner. By using a refined mesh, no strong differences are seen on the helium path: it goes from the diffuser to along the tank walls. One can see that velocities are better capted in the middle of ullage volume.

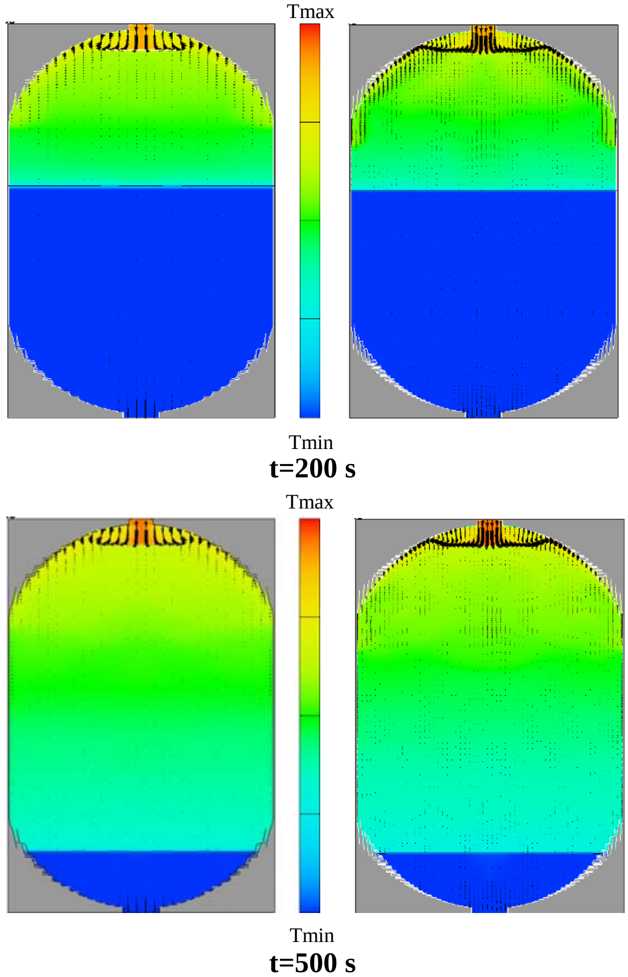


Figure 13 : Lox Temperature Plots
Comparison versus Mesh size

SYNTHESIS

The studies performed have shown on a real case the amount of results available and the level of accuracy associated of pressurization tools compared to real data (Ariane 5 flight). It allows us to:

- Consolidate the level of validity of each method,
- Apply the right tool for the right purpose at each level of a project
- Identify the way to follow for tools improvement and rules to be used
- To have a capability to deal with complex geometry and phenomenon for detailed analysis.

Moreover, as Flow3D® shows a good capability to perform this kind of estimates, then we plan to go further and continue the analysis about this topic dealing with propellant and its own vapor, 3D analysis…

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