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Cryogenic flows end-to-end fluid simulations for CALLISTO demonstrator

LE MARTELOT Sébastien[1]*, CLIQUET MORENO Elisa[1], FRENOY Olivier[1], LIENART Thomas[1], OPP Lukas[2], TERAKADO Daiki[3], HIRAIWA Tetsuo[3]

[1]*CNES, 52 rue Jacques Hillairet, 75012 Paris Cedex, France*
**sebastien.lemartelot@cnes.fr*
[2]*DLR, Robert-Hooke-Str. 7, 28359 Bremen, Germany*
[3]*JAXA Tsukuba Space Center, 2-1-1 Sengen, Tsukuba-shi, Ibaraki 305-8505, Shengen*

Abstract

The CALLISTO vehicle is a flight demonstrator for future reusable launcher stages. The program involves three countries and their space organizations: CNES for France, DLR for Germany and JAXA for Japan. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches. The challenge is to develop, all along the project, the skills of the partners. This know-how includes Products and Vehicle design, Ground Segment set up, and post-flight operations for Vehicle recovery then reuse. Designing and operating such a vehicle and its associated launch base requires a perfect match between vehicle needs and ground equipment specifications.
In this paper, LOx and LH2 flow behavior during three major phases before lift-off is analysed through ground/vehicle coupled simulations. The LH2 analysis is completed by and compared to a more detailed tank simulation. The results of these analyses are then used to create technical specifications for ground segment components design.

1. Introduction

The CALLISTO vehicle ([1][2]) is a reduced scale flight demonstrator for future reusable launcher stages developed jointly by CNES, DLR and JAXA: 13m height, 1.1m diameter, CALLISTO is filled with approx. 3.6t of LOx and LH2 and equipped with a JAXA engine. Its performance requirements in terms of flight domains are such that precise filling is required. Being a vertical lift-off, vertical landing demonstrator, it is equipped with cryogenic connectors that have to be disconnected sufficiently ahead of lift-off to allow a lift-off and landing pad clear of all ground segment equipment.

In this context, Ground Segment set up has to be in agreement with vehicle design, especially concerning the interface parameters and operational constraints. Thus, the main goal of this paper is to study the liquid oxygen (LOx) and liquid hydrogen (LH2) vehicle tanks filling process in order to assist the launch base design by computing coupled launch base/vehicle cryogenic flows parameters (Pressure, temperature, flow rate, etc.). The tank filling process is organized in three major steps: first pre-cooling & filling, then contingency waiting phase and top-up of the on-board tanks.

In order to compute the interface data, the complete CALLISTO fluid ground segment equipment (FGSE) and vehicle cryogenic lines are modeled including pipes, valves and tank. The details of this modeling are given in paragraph 2. The vehicle tanks' two-phase flow behavior being the main driver of the filling process, especially on hydrogen side, two computations of LH2 filling process results are detailed and discussed in this document in paragraph 3. The first one is the ground/vehicle end-to-end coupled simulation done by CNES whereas the second one is dedicated to the LH2 tank internal complex behaviour. This second calculation has been done by DLR, the product designer of this tank.

These two LH2 side analysis are completed by the ground/vehicle end-to-end coupled simulation of the LOx side.

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The focus on LH2 side is due to the fact that there is no collection of vented hydrogen and that it was deemed important to have several independent assessments of the order of magnitude of venting flow rate in order to assess the H2 cloud behavior. This paper thus mostly focusses on the results obtained for the LH2 tank in pre-flight phase but the models are also used to predict the behavior of both tanks in post flight phases.

The end-to-end computation has been done using the CARMEN platform [3], a flows system analysis software developed and maintained in the CNES propulsion system teams while the DLR calculation has been done with an improved version of EcosimPro.

The last part of this article deals with the interface requirements writing using the previous calculations results. These requirements have been transmitted to the Ground Segment Equipment teams in order to design and select the ground segment components and structures.

2. CALLISTO launch base and vehicle cryogenic configuration before lift-off

Until lift-off, the CALLISTO vehicle is connected to the to the liquid oxygen (LOx) and liquid hydrogen (LH2) ground storage in order to be able to do the chill down, filling and top-up processes. Figure 1 presents simplified schematics of the cryogenic pipes, valves and interfaces leading from the ground storages to the vehicle tanks.

The LOx and LH2 layouts are symmetrical. A first pipe connects the ground storage to the control valve. The goal of this valve is to control the flow rate coming from the ground storage to the vehicle. Connected to this valve outlet, a second pipe leads to the vehicle interface. This interface allows connecting the ground pipe to the vehicle pipes.

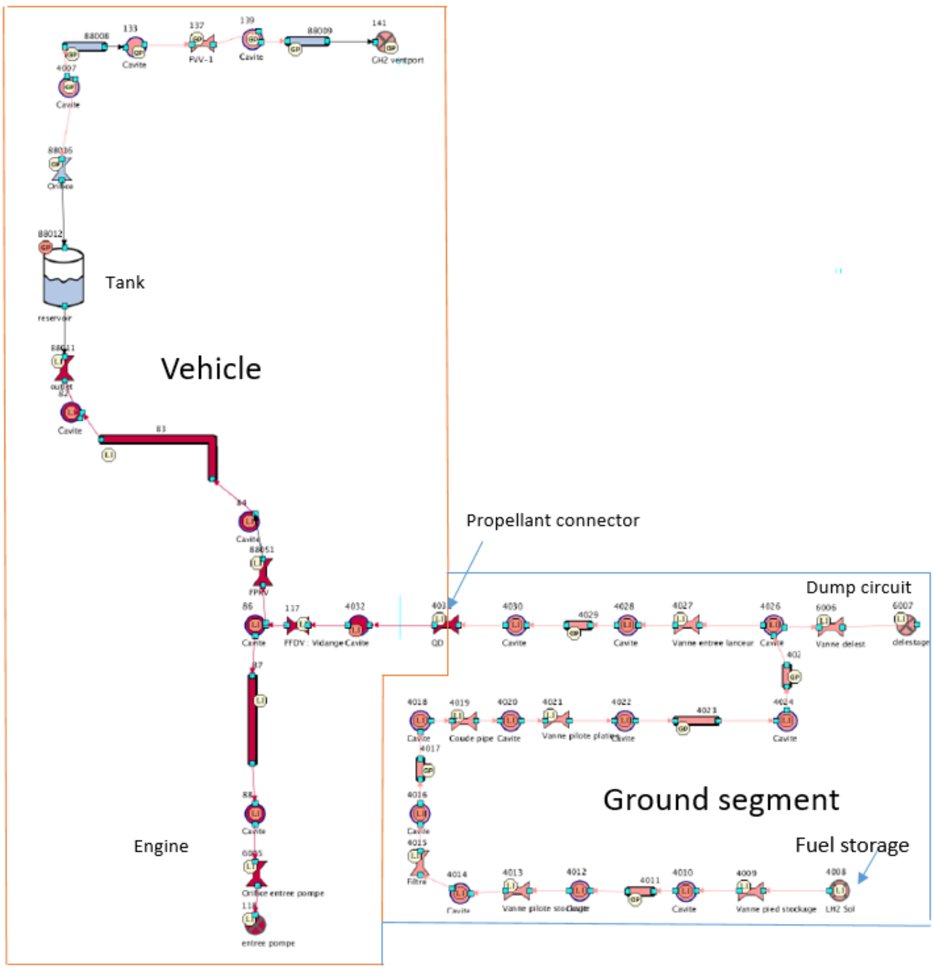

Figure 1 : CALLISTO ground and vehicle cryogenic flow schematics as modelled in end-to-end computation (LH2 Side is shown but LOX side is symmetric)

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Inside the vehicle, the liquid cryogenic flow coming from the ground segment facilities is separated in two flows: towards the tank and towards the engine.

The flow going towards the tank is used for tank chill down, filling and topping-up. This flow is controlled by the (O/F)TV on/off valve (named FFDV on Figure 1) used to isolate the tank during the waiting phase. The other vehicle pipe purpose during filling, waiting and top-up is to perform engine chill-down and keep the engine cool until lift-off. During the filling process, both tanks venting valves are open and connected to the outside environment.

Using these components, the several steps described in the introduction (First filling, waiting phase and top-up of the on-board tanks) have been computed with the following sequence:

1. First filling after tank chill-down
    a. OTV (Oxygen tank Valve) is open
    b. FTV (Fuel Tank Valve) is open
    c. Ground control valves : fully opened
2. Waiting phase
    a. OTV is closed
    b. FTV is closed
    c. Ground control valves: low opening (engine chill-down flowrate)
3. Top-up phase = same valves positions as First filling

3. Liquid hydrogen (LH2) flow simulation

In this paragraph, two calculations of the LH2 flow are presented, a ground/vehicle end-to-end coupled simulation and a dedicated liquid hydrogen tank simulation. The end-to-end simulation goal is to determine interface data while liquid hydrogen tank simulation is focused on the hydrogen behaviour in the tank. In order to be able to compare the results, the two computations used the same initial conditions, boundary conditions and sequence:

- Initial conditions
    - Post chill down conditions in tanks and pipes (liquid flow)
    - FTV and OTV valves open
    - Ground control valves: fully open

- Boundary conditions
    - Solar heat flux with insulation layer on the tank cylindrical parts
    - Heat flux coming from inside the vehicle on tank domes
    - Venting valves open to an atmospheric pressure
    - Ground storages: constant pressures and temperatures
    - Solar heat flux with insulation layer on ground pipes
    - No heat flux on vehicle pipes

- Sequence
    - Filling until target mass is loaded
    - Waiting phase: 5000s (this waiting phase is a contingency for off nominal scenarios like poor weather or delays in the countdown sequence for miscellaneous reasons).
    - Top-up until target mass is re-obtained

3.1 Ground/vehicle end-to-end coupled simulation

These simulations have been done with the CARMEN platform [3] with a custom CNES made component in order to simulate the complex flow in the tank. This tank component is a 1.5D representation of the volume with liquid, gas, phase change, heat transfer, convection and conduction taken into account. The liquid pipes and valves on ground or

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in the vehicle consider incompressible flow while gas volume (venting lines and tank ullage) use the perfect gas approximation.
Considering the sequence and conditions detailed in the previous paragraph (3), the following results are obtained.

- LH2 tank: liquid volume

Figure 2 shows the liquid hydrogen mass in the tank as a function of time. The loading duration is around 1800s followed by 5000s of waiting phase contingency before the ultimate top-up phase.

Figure 2– Loaded mass in vehicle LH2 tank

This mass is injected in the tank through the filling & drain port. To ensure liquid phase at tank inlet, Figure 3 and Figure 4 show the pressure and temperature of the hydrogen at tank inlet.

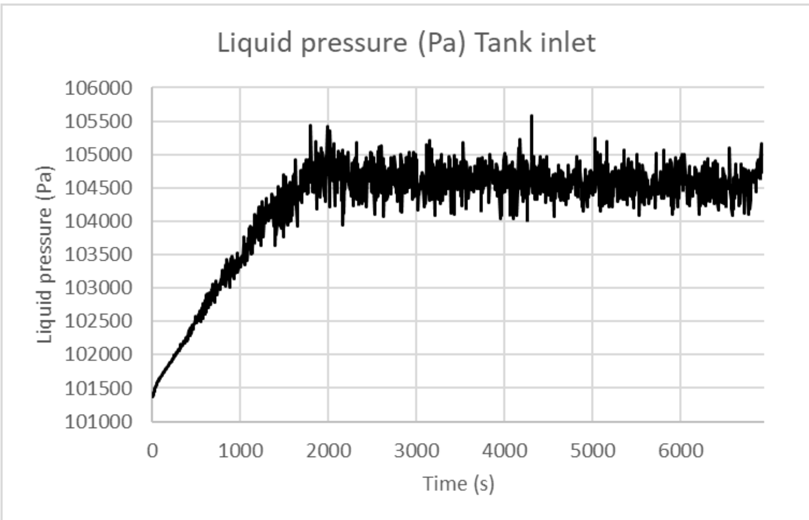

Figure 3 – LH2 pressure at tank inlet

The pressure at tank inlet is following the expected increased due to the hydrostatic pressure. Then, once the first filling is done (~1800s) the pressure is very slowly decreasing due to boiling during waiting phase.

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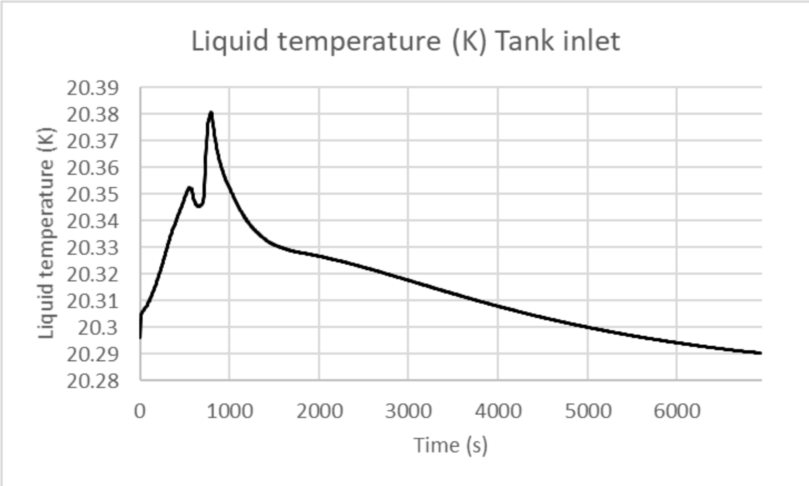

Figure 4 – LH2 temperature at tank inlet

By comparing these data to the saturation temperature curve of hydrogen, two separate behaviors can be noticed on Figure 4. During the first behavior (until ~900s), saturated hydrogen is injected in the tank. Once there is enough liquid in the tank, the boiling interface is far enough from the tank inlet for the convection loops to be the major heat transfer mechanism. Therefore, the temperature at tank inlet is slowly converging (second behavior) towards LH2 temperature at vehicle inlet.

- LH2 tank: Ullage
The same analysis is performed at the other LH2 tank interface, the venting port. Figure 5 shows the GH2 flowrate flowing out of the tank. A check valve on tank vent line was considered in this computation for numerical reasons.

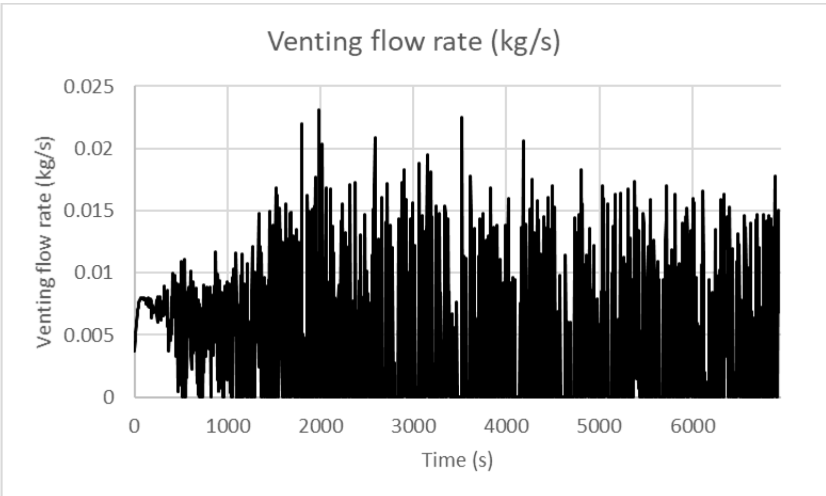

Figure 5 – GH2 flowrate at LH2 tank venting orifice

On this Figure, the two behaviors noticed on Figure 4 (Tank inlet temperature) are visible. Indeed, until the end of the saturated phase the flow rate has a maximum value of 10g/s whereas during the remaining time maximum flow rate can reach up to 22g/s. This flow being computed with 0D approximation, only the low frequency behavior is deemed representative. Developments are on-going to improve the representativeness of the model for what concerns the vaporization inside the full liquid bulk. The high frequency is either physical due to a too low pressure drop in the venting line or numerical due to sampling rate.
Knowing the flow-rate, it is now of interest to study the thermodynamic state of the GH2 gas in ullage at the venting port. Figure 6 and Figure 7 show the gas pressure and the temperature at LH2 tank venting port.

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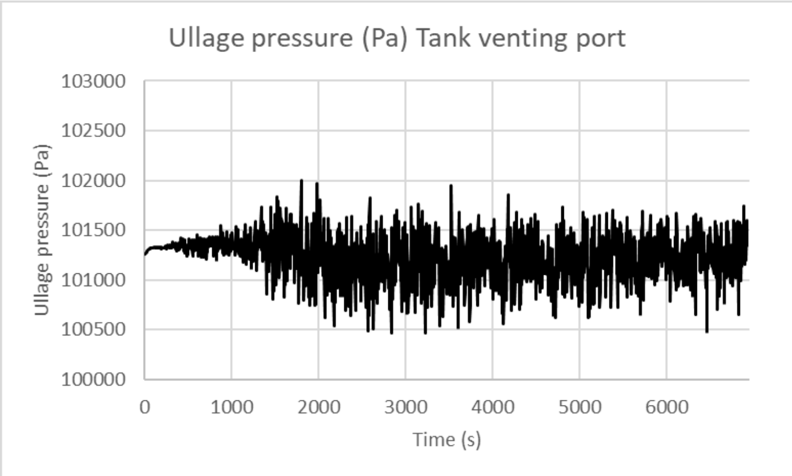

Figure 6 – GH2 pressure at LH2 tank venting orifice

The gas pressure mean value is very stable (1000 Pa changes) with a noticeable drop at the end of the filling gas, the gas being less compressed than during the filling.

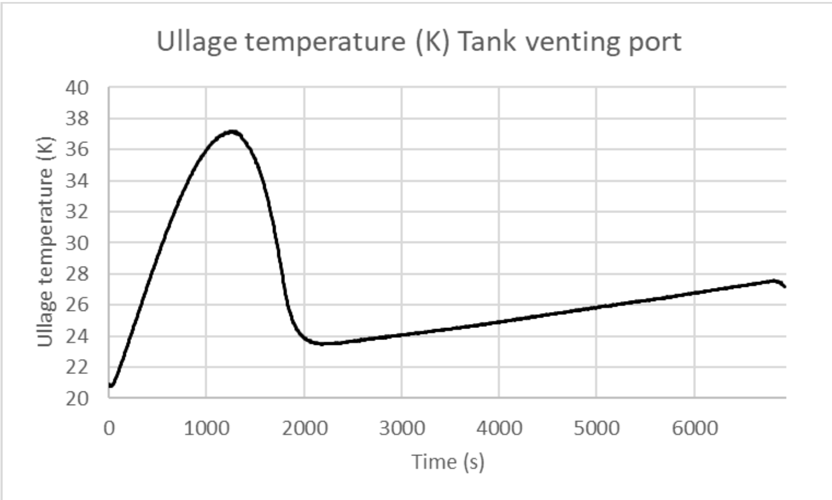

Figure 7 – GH2 temperature at LH2 tank venting orifice

Concerning the temperature at the venting orifice (Figure 7), a clear change of behaviour can be noticed between the end of the filling phase (~ 1800s) and the waiting phase. The ullage is not compressed anymore leading to a temperature drop modified only by heat flux coming from the wall and the associated boiling during the waiting phase.

The flow behavior inside the tank being as expected except for these high frequency fluctuations, the remaining point of interest is the flow at the LH2 interface.

- Interface results

The three phases studied in this paper are strongly visible in Figure 8 where one can see the LH2 flowrate coming in vehicle during filling (high flow rate), waiting (low flow rate for engine chill-down only) and top-up (high flow rate). The flowrate being controlled by LH2 ground control valve opening variation.

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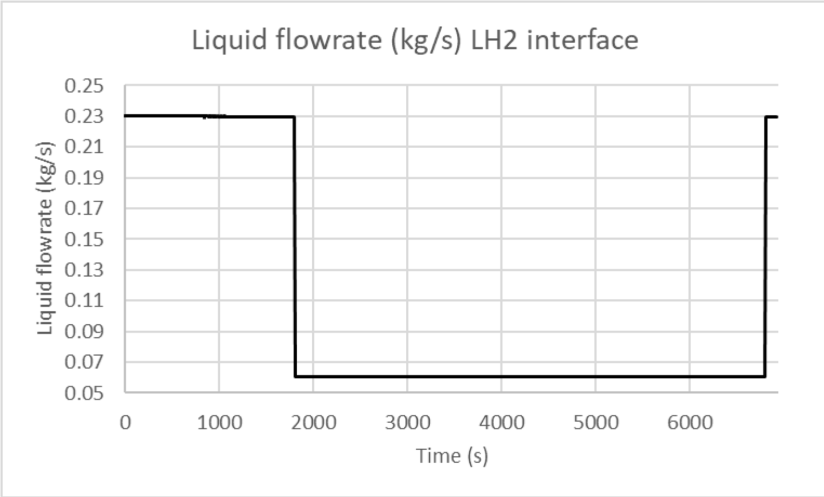

Figure 8 – LH2 flowrate at vehicle LH2 interface

As for the tank, a pressure/temperature analysis at this location has been done in order to verify if liquid hydrogen is available at the vehicle LH2 interface during all phases. Figure 9 and Figure 10 shows pressure and temperature at this location.

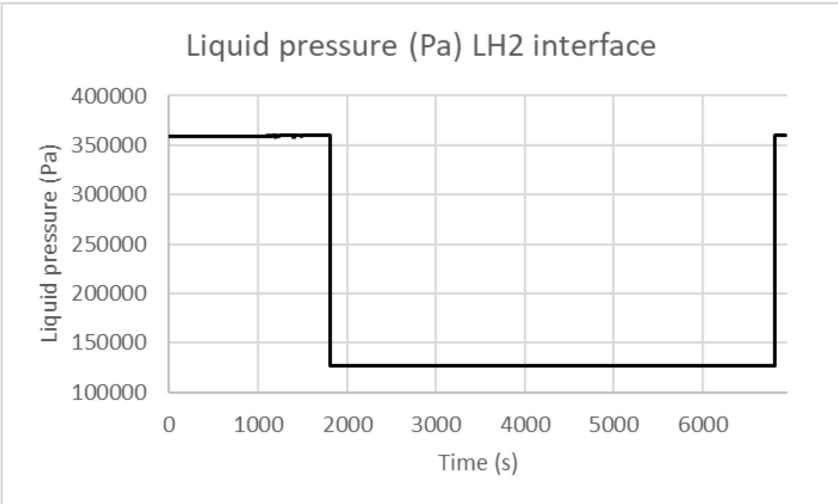

Figure 9 – LH2 Pressure at vehicle LH2 interface

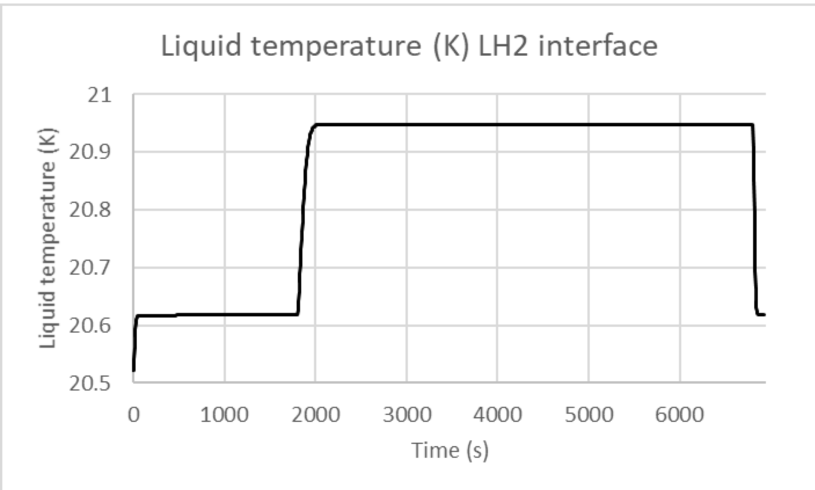

Figure 10 – LH2 temperature at vehicle LH2 interface

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The impact of the LH2 ground control valve opening is clearly visible in Figure 9 and Figure 10 where the drop in pressure is important leading to lower speed in the ground pipe, which lead to an increase of temperature to the external heat flux.

A comparison with the hydrogen saturation curve showed that the hydrogen stayed in liquid phase with a very small margin during waiting phase. This result has now been taken into account in order to improve the sequence in order to have a higher margin to saturation.

3.2 Liquid hydrogen (LH2) tank simulation

To analyze the functional and thermal behavior of the tank, a 1D EcosimPro / ESPSS model has been developed. The model features the tank with outlet equipment i.e. anti-vortex device, sieve and confusor, the tank skirts and the PU-foam acting as insulation material applied to all outer surfaces as well as certain inner surfaces e.g. bulkheads and inner skirt walls. All necessary peripheral components like valves and lines are also included considering pressure drops. The model is capable of capturing phase change, boiling and evaporation mass flows as well as heat transfer between the phases and the walls with all fluids modeled as real fluids. In this case, five liquid and five gaseous control volumes are used with five thermal nodes in the cylindrical tank section and in the upper and lower dome respectively. A more detailed description of the model is given in [4].

The case presented in this paper is set up as follows:

- Initial conditions
    - Liquid and gaseous volumes both initialized in gaseous regime set to 20.4 K only containing Helium as a non-condensable gas
    - Tank structure set to 20.4 K
    - Insulation layer with linear temperature profile from 20.4 K at the innermost edge to ambient temperature (293.15 K) at the outermost edge
    - FTV open / Venting valve open

- Boundary conditions
    - Fixed incoming flow rate of 0.19 kg/s until target propellant mass is reached. 0 kg/s during waiting phase of 5000 s. Top-off flow rate of 0.19 kg/s applied at the end of the waiting phase
    - Loading boundary condition set to constant pressure of 1.1e5 Pa and 20.3 K with flow rate limiter
    - Venting boundary condition set to constant pressure of 1 atm and 293.15 K
    - Thermal environment considers natural convection, solar radiation, induced convection inside engine bay and equipment compartments, infrared radiation and convective heat imposed at the upper and lower skirt flanges

- Liquid mass

During the loading procedure, the tank gets filled using the lower tank port. A constant incoming flow rate of 0.19 kg/s at a constant LH2 temperature of 20.3 K is applied by the boundary condition. The mass of the propellant during the filling, waiting and top-off phase is shown in Figure *11*.

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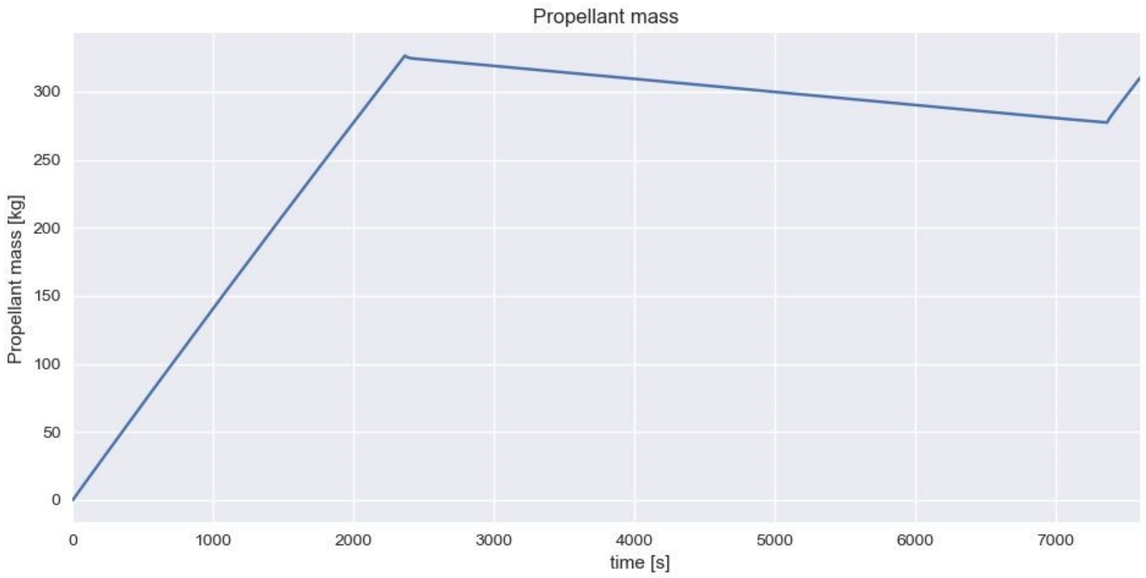

Figure 11 - Propellant mass

At the beginning of the simulation, the liquid mass immediately starts to rise until reaching the target mass after 2364 s. After reaching its peak, the liquid mass starts to boil-off with a rate of 34.5 kg/h until being topped up after 5000s at ambient pressure.

- Ullage pressure

Figure *12* depicts the ullage pressure at the venting port. At the beginning of the loading procedure, the tank pressure shows a peak due to initial film boiling of the liquid entering the tank to chill down the tank wall, that gets heated by the energy stored in the thermal insulation layer. Following that peak, the tank pressure stabilizes at around 1.06 bar. A distinct wave-like pattern can be observed that is tied to numerical effects when the liquid starts wetting another tank wall segment.
After the loading sequence is finished at 2364 s, the tank pressure decreases due to a decrease in boil-off rate and stabilizes at around 1.015 bar. At top-off procedure initiation, the tank pressure rises to the same level as at the end of the loading process.

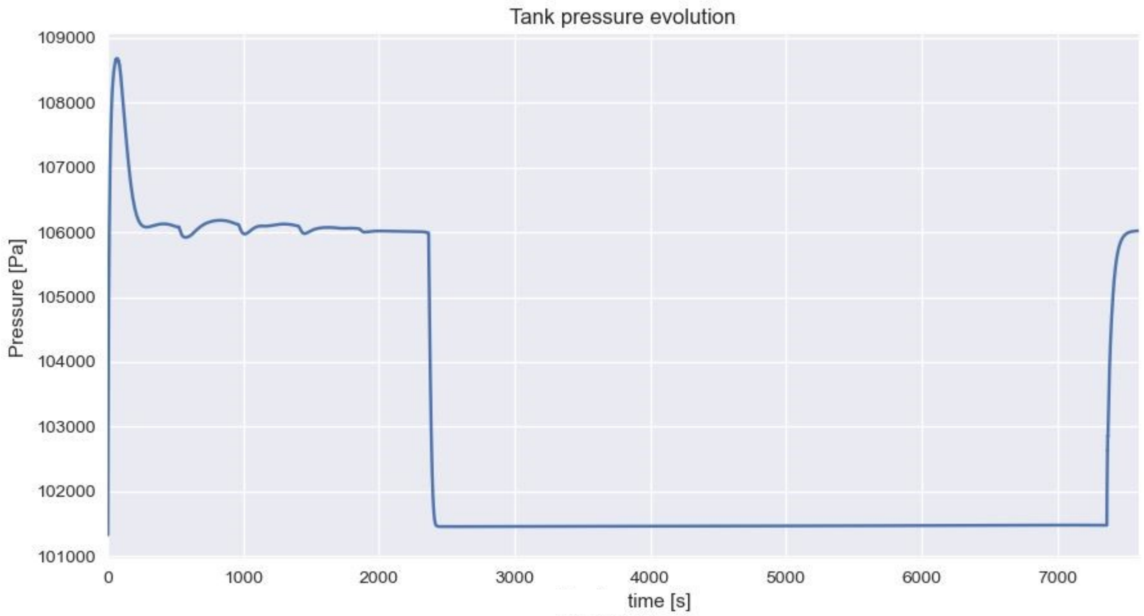

Figure 12 - Tank ullage pressure

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- Liquid pressure

The pressure of the first liquid control volume inside the tank has been plotted in Figure *13*.

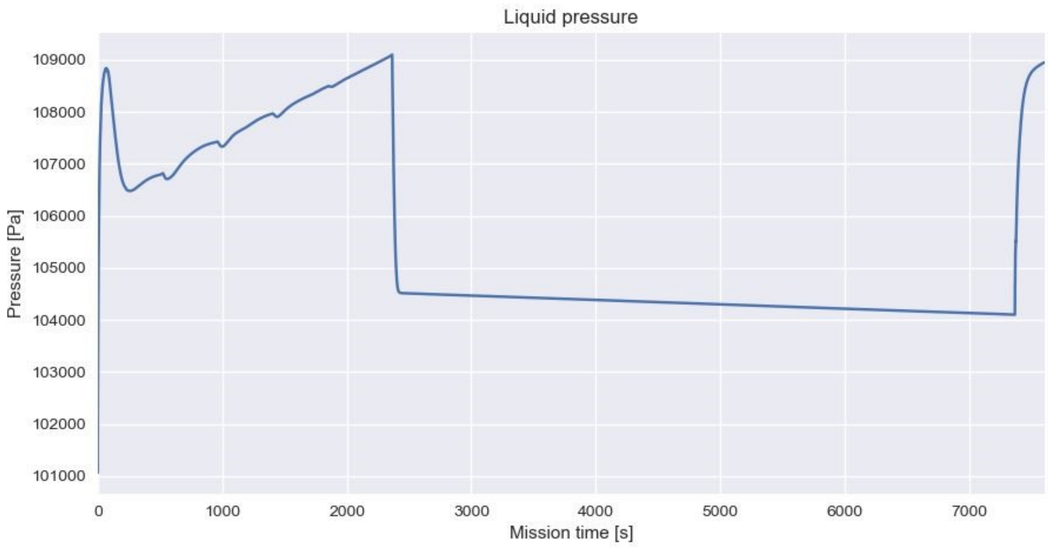

Figure 13 - Liquid pressure of first liquid control volume

At the beginning of the filling process, the liquid pressure rises due to the rise in ullage pressure. Following that peak, the liquid pressure increases linearly due to the rise of hydrostatic pressure in the liquid column. When the filling process ends, the liquid pressure decreases by the same amount as the ullage tank pressure. During the waiting phase, the liquid pressure decreases linearly, which corresponds to the decrease in liquid column height thus reducing the hydrostatic pressure.

- Liquid temperature

Figure *14* shows the liquid temperature of the first control volume.

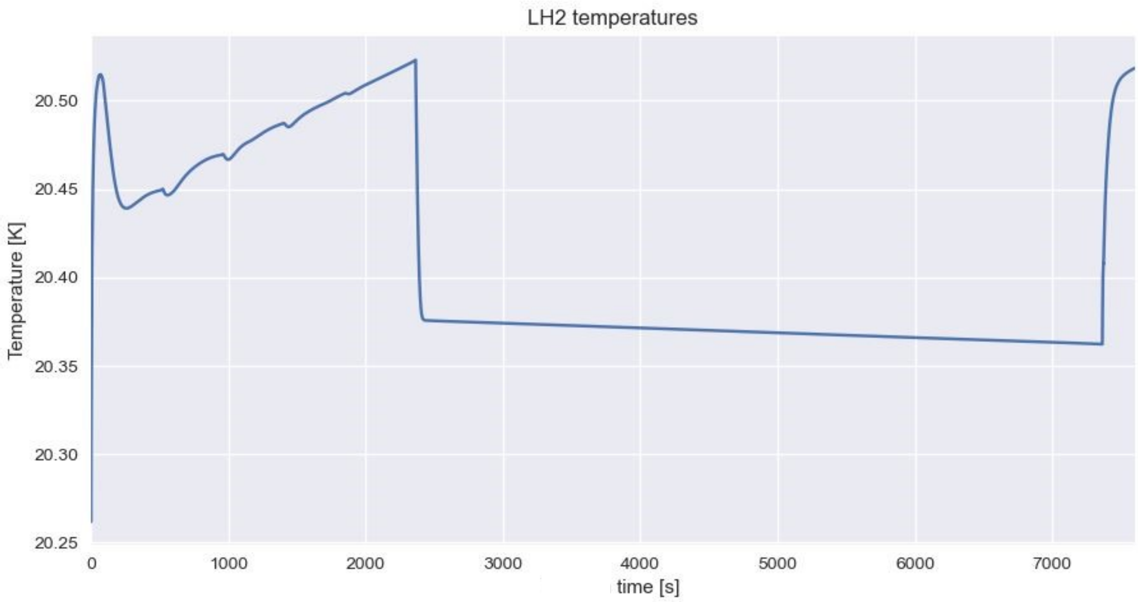

Figure 14 - Liquid temperature of first liquid control volume

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After the filling process has been started, the temperature of the liquid phase increases, which can be explained by the removal of wall heat energy by boiling. Subsequently, the temperature rises in a linear manner due to an increase in hydrostatic pressure leading to an increase in saturation temperature.
As soon as the loading procedure is finished, the temperature of the liquid decreases because the saturation temperature drops due to decreasing liquid pressure.

- Venting flow rate

The venting mass flow rate is depicted in Figure *15*. After an initial peak due to strong initial boiling, the flow rate drops to ~ 0.05 kg/s and shows a slight increase to just below 0.06 kg/s at the end of the filling procedure. When tank loading is finished, the venting flow rate drops significantly to ~ 0.01 kg/s which corresponds to the boil-off mass flow rate during the waiting phase.

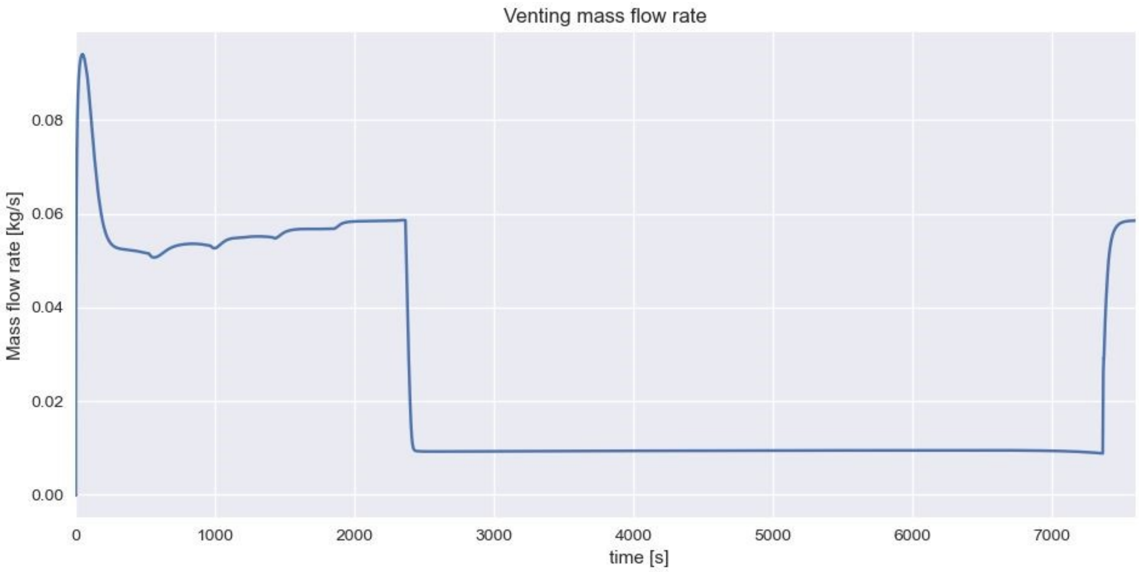

Figure 15 - Venting mass flow rate

- Ullage temperature

The ullage temperature rises at the beginning of the simulation due to thermal energy stored in the thermal insulation layer at the beginning of the simulation. After reaching its peak, the temperature starts decreasing due to the cold vapor of the vaporized LH2. Again, the number of control volumes introduces a step-like pattern in the temperature profile causing a distinct step when the liquid column reaches another wall segment. After the loading process is finished, the temperature rises due to incoming heat from the thermal insulation.

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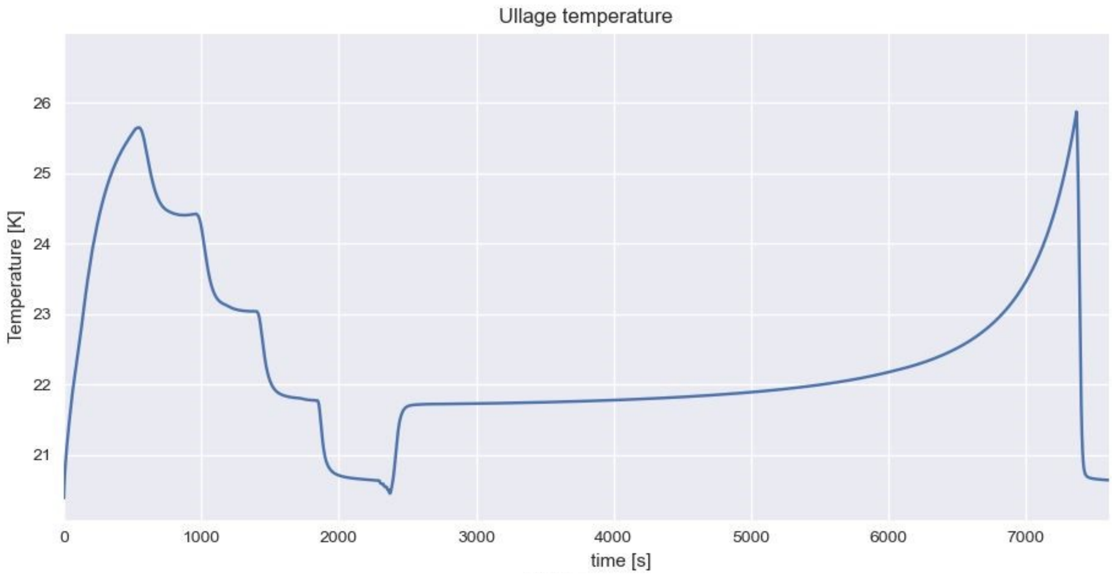

Figure 16 - Ullage gas temperature

3.3 LH2 flow discussion

By comparison, between CNES (See 3.1) and DLR (See 3.2) one can notice that the two methods gave the same results during the waiting phase but show some differences during the first filling phase.

The first minor difference is the filling duration. DLR filling duration is a bit longer only because the imposed filling flow rate is equal to the mean value of CNES calculation.

The second one is major and more complex. Indeed, the ullage pressure shows a visible difference. The two hydrostatic profiles are similar except that the one from DLR calculations shows an offset of around 5kPa during filling. The offset is thought to be linked to increased LH2 boil-off during this phase. CNES ullage shows no increased boil-off during the filling phase, therefore the boil-off is thought to be under-estimated by the model.

This difference lead to lower ullage temperature due to higher boil-off vapor close to saturation temperature. Moreover, the higher pressure in ullage creates higher venting flowrate and, thus, less heating due to external fluxes.

The last difference of importance is the peak visible in DLRs calculation at the beginning of the simulation, which is caused by increased boiling at the start of the simulation, and is linked to a slight difference in the initial conditions modeling of the wall temperature.

Therefore, considering that the main objective of CNES end-to-end computation is to determine acceptable ranges of flowrate, pressure and temperature at the vehicle interface, as well as to perform some trade-off on Ground Segment Equipment choices, the differences have been determined of minor importance regarding these specific parameters.
Even though, there is still work to be done to improve accuracy in ullage, CNES and DLR calculations are considered in agreement with regard to this high level needs .

4. Liquid oxygen (Lox) flow simulation

The end-to-end simulation was also done for LOX side (with the same flow schematic and different parameters including time span of waiting phase set arbitrarily to ~3600s in this simulation).
The oxygen flow inside the tank being as expected with a strong margin with regards to saturation the paper only details the interface data required to write a technical specification for the launch base team.

Thus, Figure 17 shows the liquid oxygen flow rate at vehicle Lox interface.

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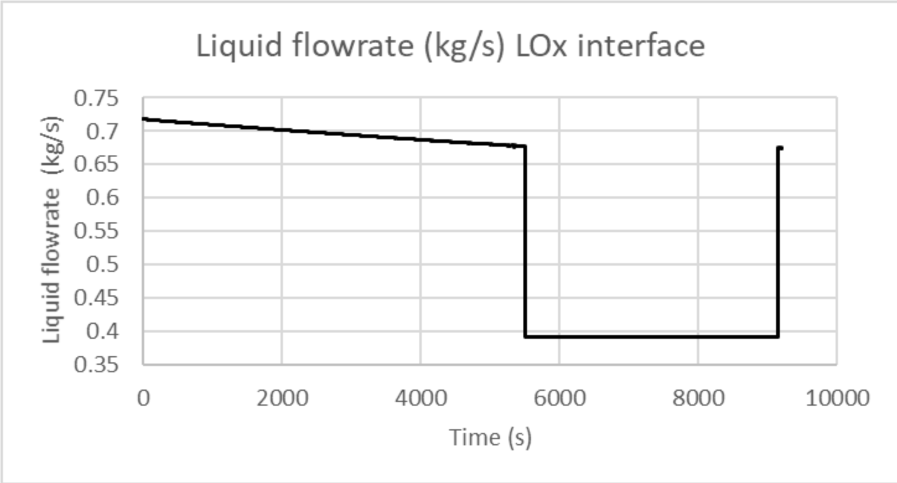

Figure 17 - LOx flowrate at vehicle LOx interface

As for the LH2 study, the impact of the ground LOx control valve is clearly visible, separating the three phases.

In order to check if the oxygen is liquid at the interface, pressure and temperature at this location is shown in Figure 18 and Figure 19.

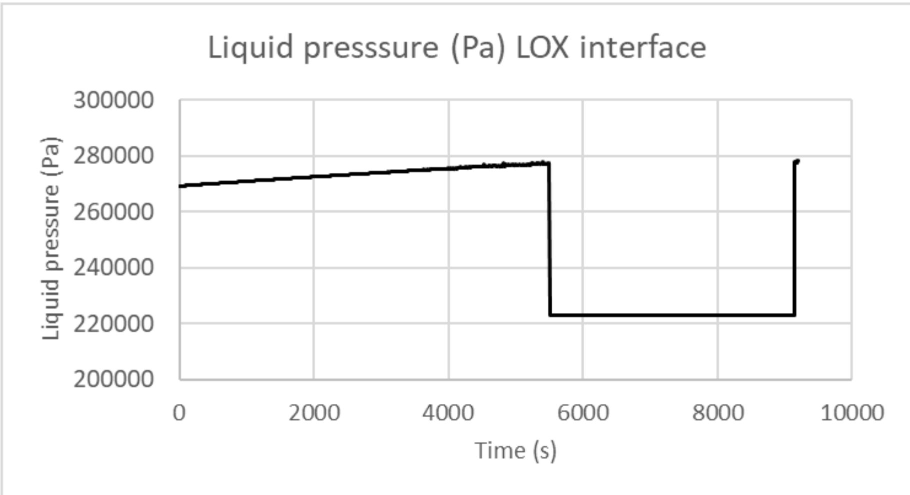

Figure 18 - LOx pressure at vehicle LOx interface

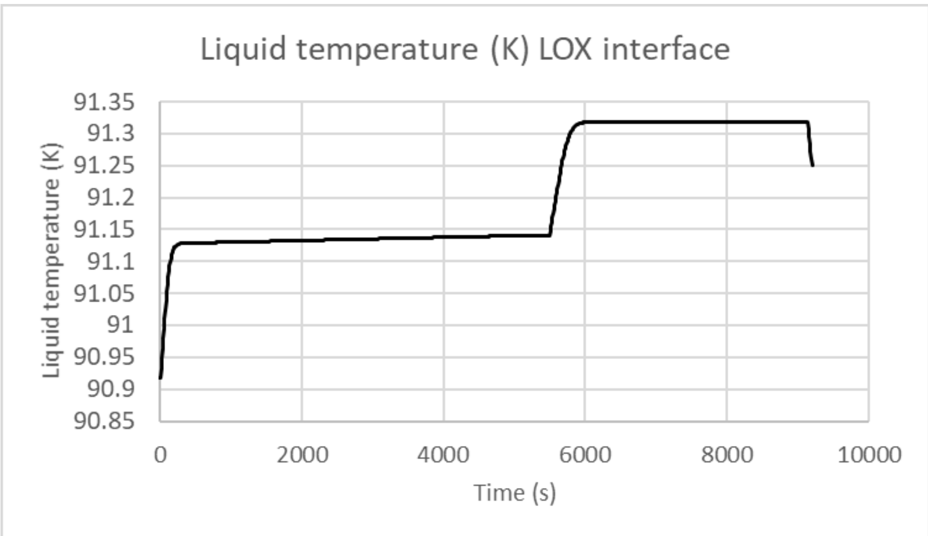

Figure 19 - LOx temperature at vehicle LOx interface

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By comparing these curves to the oxygen saturation curve, the analysis showed that sufficient margin is obtained on LOx side.

5. From calculations to technical specifications

The LOx and LH2 end-to-end simulators supported the technical specification of Ground Segment Schematics & Equipment. It was used to:

- perform trade-off on valves location and in particular dump circuit,
- perform parametric studies of pipe diameter,
- assess impact of parameters that are uncertain in early development phase like lines length and thermal heat fluxes
- Simulate various possible sequence options for managing engine chill down and tank top-up

Those studies allowed to identify the best compromise between performance (vehicle interface pressure, temperature and flow rate), COTS choice (flow rate tenability range) and practical constraints like weight of the pipes that are held by cryo-arms that need to be removed ahead of lift-off.

At the end, the GSE fluidics schematics was frozen and tables similar to the one shown in Table 1 were established for interface between Ground Segment and Vehicle. Specification of lines, orifices and valves compatible with these operating needs where issued.

Expected			Limit curves					
Temp	Pressure	Flow Rate Min Max	Temp		Pressure		Flow Rate	
			Min	Max	Min	Max	Min	Max

Table 1 – Example of technical specifications table

The simulator will also be used in further development phases: it will be updated based on vehicle product design update, thermal loads and pre-flight and post flight sequences fine-tuning. It will also allow to simulate off nominal cases.

6. Conclusion

When building a ground segment for a new space vehicle, it is mandatory to obtain reliable estimations of the vehicle needs in terms of pressure, temperature and flowrate for every fluids delivered to rocket. To obtain this data, one way is to create a numerical model of all the fluidics components of interests in order to be able to simulate the flow inside these components.

This method has been used in this paper to simulate the cryogenic LH2 and LOX flows coming from the ground facility storages to the CALLISTO vehicle. The LH2 results have been compared to the product owner (DLR) and allowed to secure the estimation of the boil-off rate.

Even though the LH2 calculations showed some differences, especially in the boil-off approximation, the pressures in the tank where close enough to consolidate LH2 flow rate need at vehicle interface. Concerning pressure and temperature at interface, limitations of allowable flow rate during waiting phase have been noticed.

The LOx calculations showed no issue or limitation for the sequence chosen in this paper.

Finally, the end-to-end simulators have been used to perform studies contributing to technical specifications of the ground segment equipment.

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