Behaviour of liquid hydrogen in the tank of cryogenic upper stage during launch preparation and flight

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Abstract

Ariane 5 uses a cryogenic upper stage (ESC-A) which means that the used propellants are liquid oxygen (LOX) and liquid hydrogen (LH_2). The different phases (flight preparation phase, main stage and upper stage flight phase) are described and the specific challenges focused on the hydrogen tank are highlighted. The occured physical effects are explained and some specific equations are given. Additionally two tools are shortly presented to analyze the three different phases.

1. Introduction

Ariane 5 uses a cryogenic upper stage (ESC-A) which means that the used propellants are liquid oxygen (LOX) at nearly 90 K and liquid hydrogen (LH_2) at nearly 20 K. The mission starts with the launch preparation (the so called ground phase), followed by the lift-off and main stage (EPC) propulsive phase, the upper stage propulsive phase and the so called balistic phase where the payloads (usually two satellites) are seperated and the upper stage is passivated.

Already during the ground phase several physical effects occure and influence the tank structure and propellant behavior.

During lift-off and following main stage propulsive phase the behaviour of the liquid hydrogen is dominated by sloshing due to acceleration gradients. Just before upper stage propulsive phase a mass flow rate is needed to chill-down (cool down) the upper stage engine HM7B.

Due to entering heat fluxes into the LH_2 tank a convective flow appears and creates a hot layer near the surface and a temperature evolution in LH_2, which is called stratification.
To analyze these different phases two tools are used:

1. inhouse code, implemented in Matlab to analyze the ground and main stage propulsive phase and
2. commercial CFD software package ANSYS/FLUENT to analyze the upper stage propulsive phase.

Both tools were validated with several flights and can be used for forecast studies or post flight analysis.

2. Overview of LH_2 behavior during ground and EPC flight phase

During launch preparation several operations regarding the tank filling process (tank cooling, tank filling, topping and pressurization) take place. In Figure 1(a) the level of liquid hydrogen and the corresponding (remaining) mass for the time period between closure of the filling valve, which is just after propellant loading and topping, and ignition of the upper stage engine HM7B at K2.1 is shown. H0 is the key event for Ariane 5 lift-off.

Liquid hydrogen is filled at certain pressure (1080 ± 12 mbar) at saturated conditions. The corresponding temperature is 20.49 ± 0.04 K.

Due to ambient temperature (≈300 K) heat fluxes enter into the LH_2 tank. This results in evaporation and the remaining mass of liquid hydrogen is reduced. Between beginning of pressurization and beginning of chill-down of the upper stage engine it is assumed that no additional evaporation occurs.

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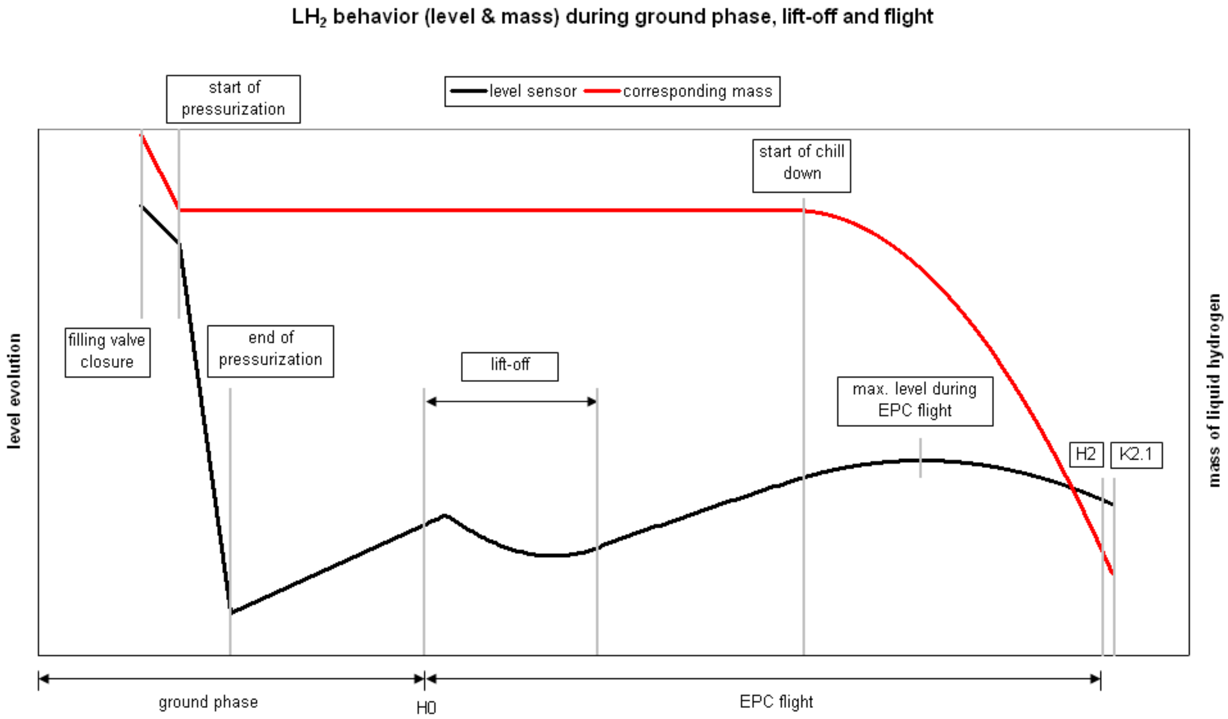
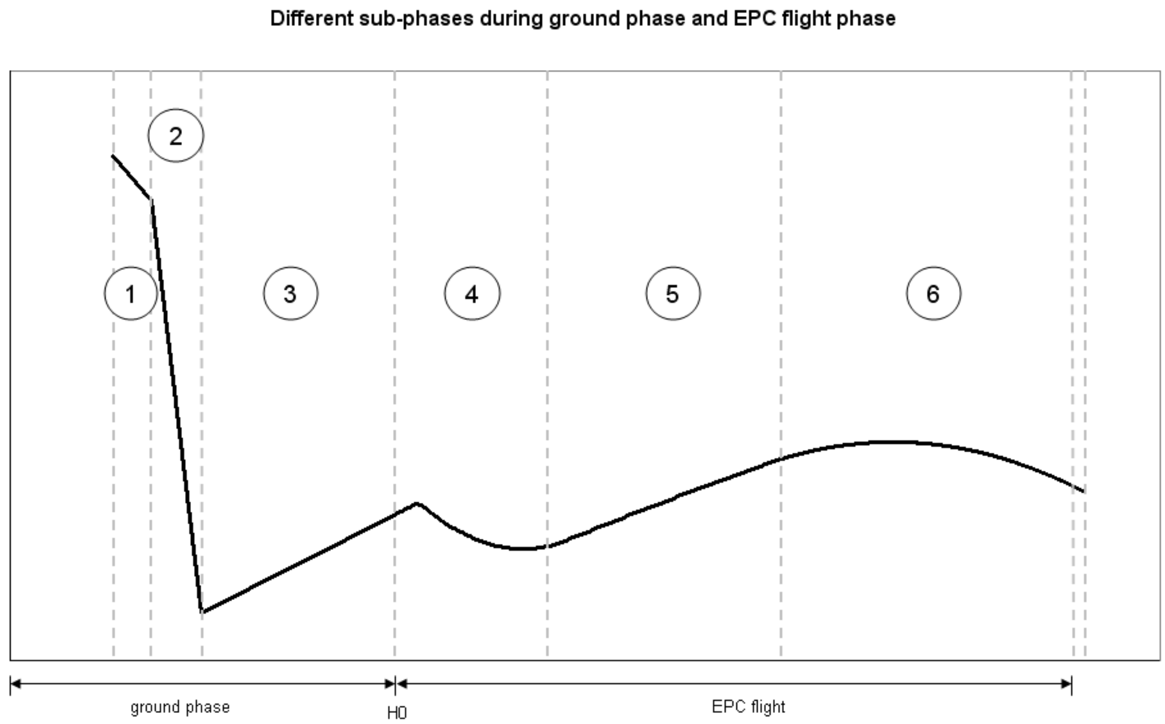


(a) Level and mass behavior



(b) Different sub-phases

Figure 1: Propellant behavior and different sub-phases during ground phase and EPC flight.

The time period between closure of the filling valve and ignition of the upper stage engine HM7B at K2.1 can be divided by 6 sub-phases which are dominated by different physical effects, Figure 1(b):

1. evaporation of LH_2, tank contraction due to temperature
2. outgassing (boiling rate), tank expansion due to relative pressure
3. heat fluxes into LH_2 tank on ground
4. pressure evolution of atmospheric pressure, heat fluxes into LH_2 tank during EPC flight
5. heat fluxes into LH_2 tank during EPC flight
6. heat fluxes into LH_2 tank during EPC flight, chill-down mass (flow rate)

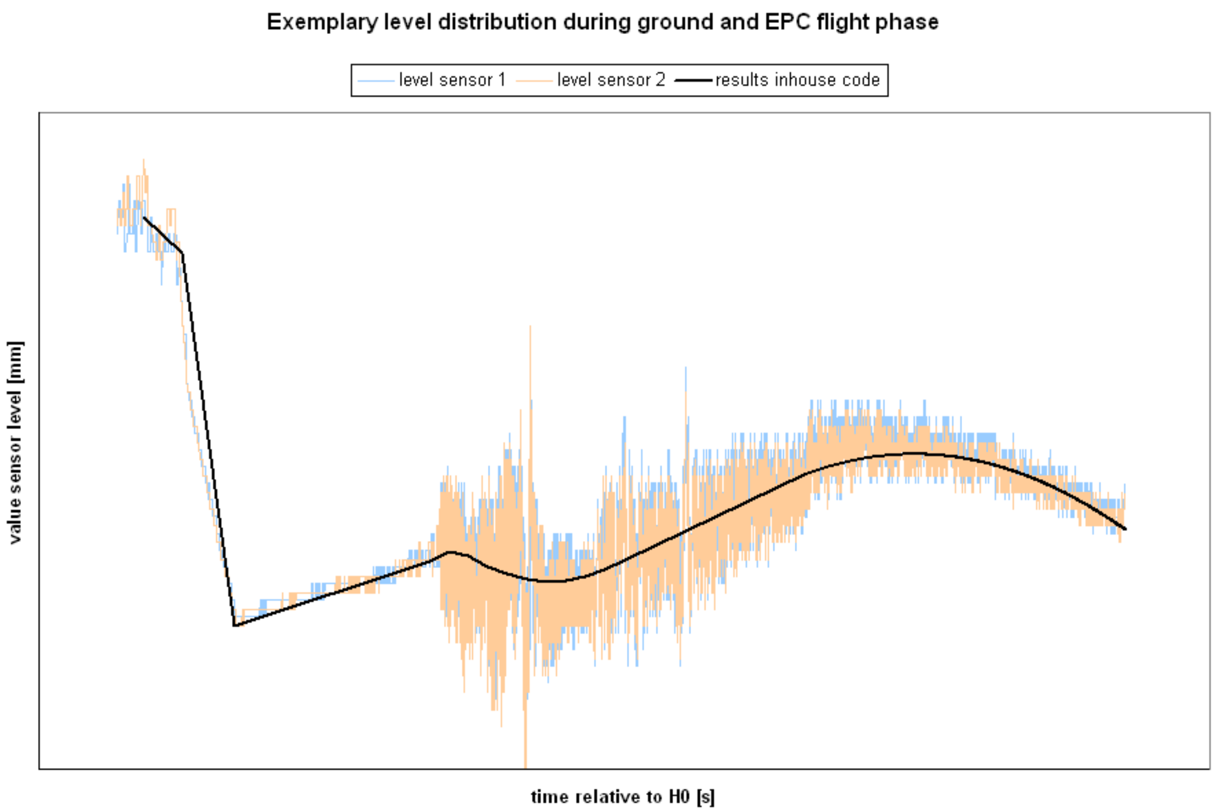


Figure 2: Exemplary level distribution.

In Figure 2 exemplary distribution of the liquid hydrogen level is shown. It can be noticed that the calculated level fits very well the flight data at every time slot.

Tank contraction

Due to low temperature the material of LH_2 tank changes its properties and the real tank volume shrinks. The volume at determined temperature can be linearly interpolated between the volume at ambient temperature (293 K) and cold temperature (20 K). The volume is then calculated as:

$$V(T) = V_{293K} \cdot \left[1 - \alpha_T \frac{293 - T}{293 - 20}\right]^3, \tag{1}$$

thereby α_T is the thermal contraction coefficient.

Tank dilatation / expansion

Due to different pressure inside and outside of the LH_2 tank the real tank volume rises. This has an impact on the level of liquid hydrogen sensor. The volume at determined delta pressure can be calculated as:

$$V(P) = V(T) \cdot [1 + \alpha_P \cdot \Delta P] , \tag{2}$$

thereby α_P is the dilatation under pressure coefficient.

Evaporation of LH_2

After closing the filling valve the hydrogen in the tank is saturated, meaning that the saturation pressure is equal to the loading pressure. At the contact surface between liquid and gaseous hydrogen additional evaporation occurs. This physical effect including phase changes is complex and needs to develop specific models.

For this reason and to keep the complexity of this model as simple as possible it is assumed that liquid hydrogen only evaporated between filling valve closure and start of pressurization (sub-phase 1 in Figure 1(b)). There is no additional evaporation until K2.1. The mass of liquid hydrogen is therefore constant between start of pressurization and start of chill-down (see Figure 1(a)).

Outgassing

Due to saturated condition during tank filling gaseous hydrogen is absorbed in liquid hydrogen. During tank pressurization with helium (sub-phase 2 in Figure 1(b)) the gaseous hydrogen is outgassed. The describing parameter is the so called boiling rate f. The resulting impact is on level of liquid hydrogen due to changing the volume of liquid and gaseous part.

Heat fluxes on ground

After pressurization the entering heat fluxes on ground $\dot{Q}_{ground}$ result in a temperature rise:

$$\dot{Q}_{ground} = \frac{mc_P \Delta T}{\Delta t} . \tag{3}$$

This corresponds in a volume and finally level increase of the liquid hydrogen (sub-phase 3 in Figure 1(b)). Although the temperature of the liquid hydrogen increases there is no additional evaporation during EPC flight phase.

In Figure 3(a) the heat fluxes on ground as an outcome from Post Flight Analysis (PFA) for several flights (mean value and the $\pm 3\sigma$ range) are shown. It can be stated that the values for each flight are inside the $\pm 3\sigma$ range.

Pressure evolution of atmospheric pressure

During EPC lift-off and flight the atmospheric pressure changes which leads to an increase of delta pressure and results in a volume change inside the LH_2 tank. From post flight analysis the pressure evolution of atmospheric pressure is shown in Figure 4(a).

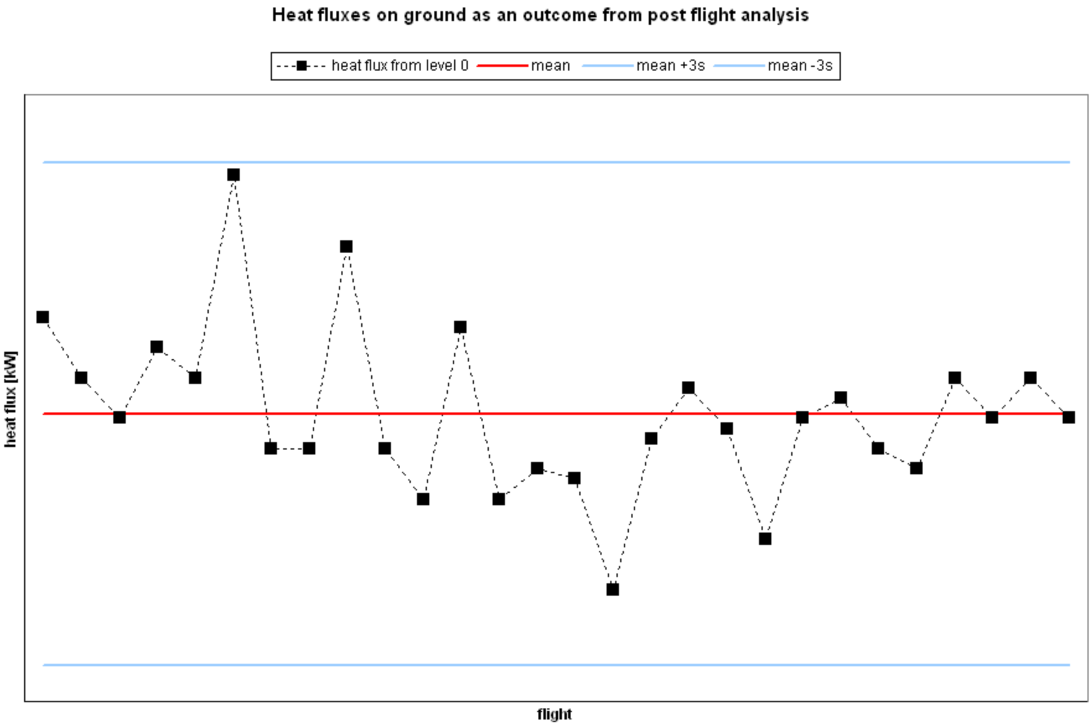
Heat fluxes into LH_2 tank during EPC flight

During EPC flight the heat fluxes are divided in three parts. For the first 60 seconds the heat fluxes are the same as for the ground phase. Between H0 + 60 s and start of chill-down the heat fluxes are validated with flight data as well as between start of chill-down of HM7B and ignition of HM7B (K2.1). These different time ranges for heat fluxes are deduced from thermal studies. The heat fluxes correspond in a volume and finally level increase of the liquid hydrogen.

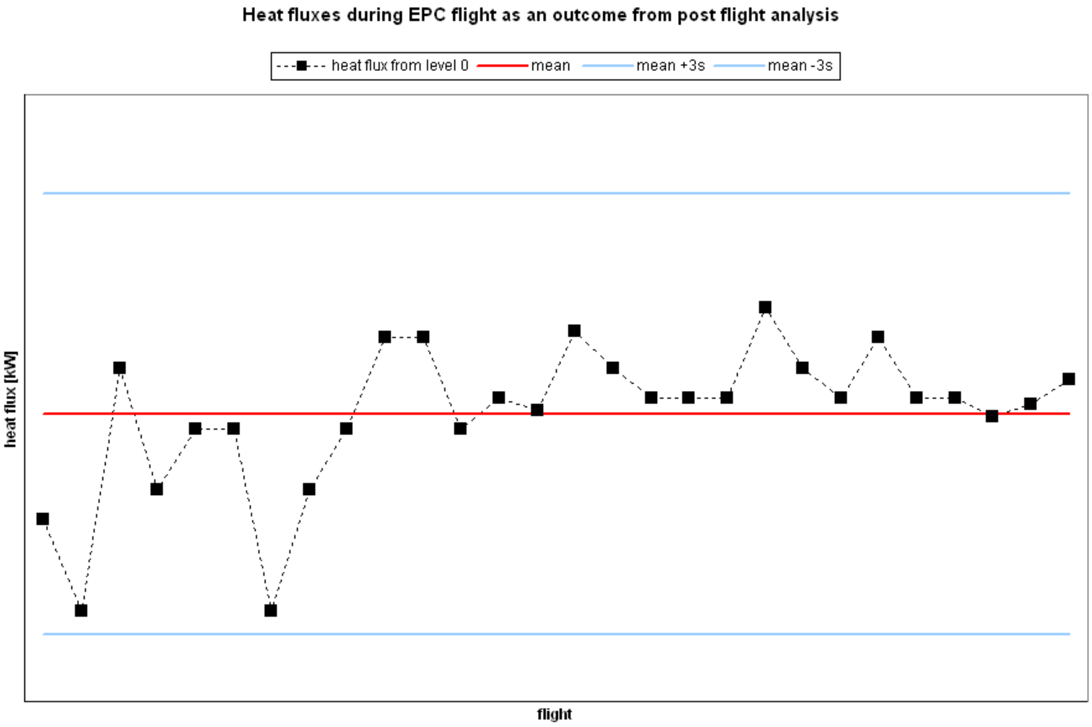
Chill-down mass flow rate HM7B

During the cill-down process the lines and valves are cooled down to ensure the needed temperature conditions. The chill-down mass flow rate is shown in Figure 4(b).

The used tool is an inhouse code, which is implemented in Matlab and validated with data from several flights.

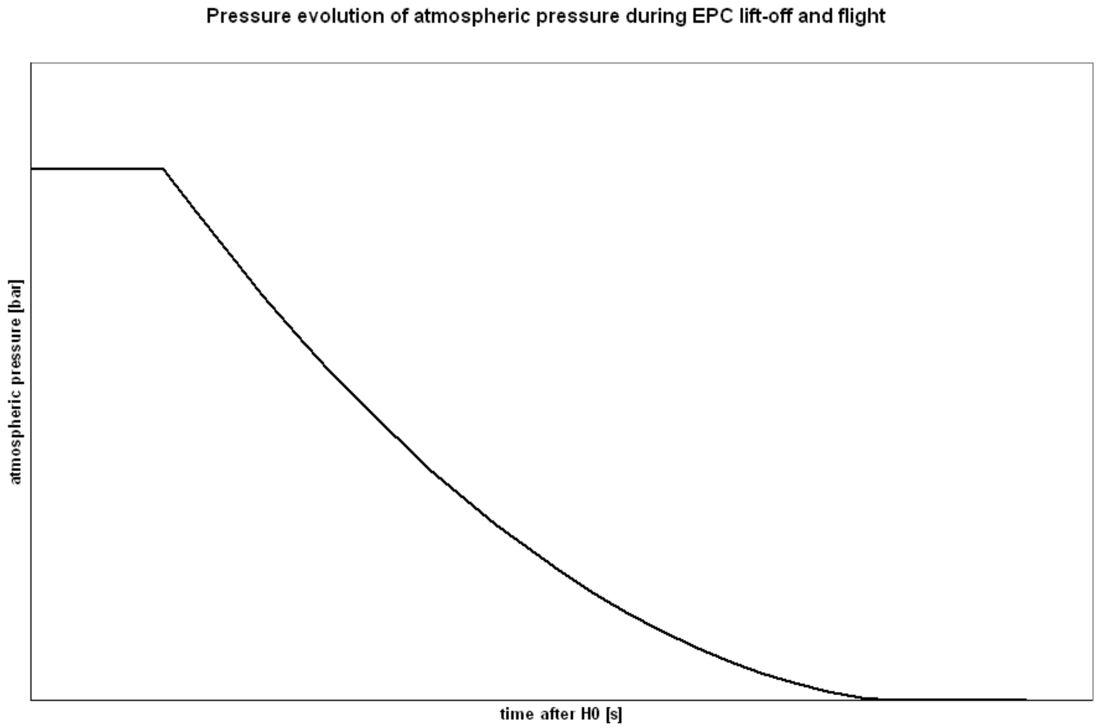


(a) Heat fluxes on ground.

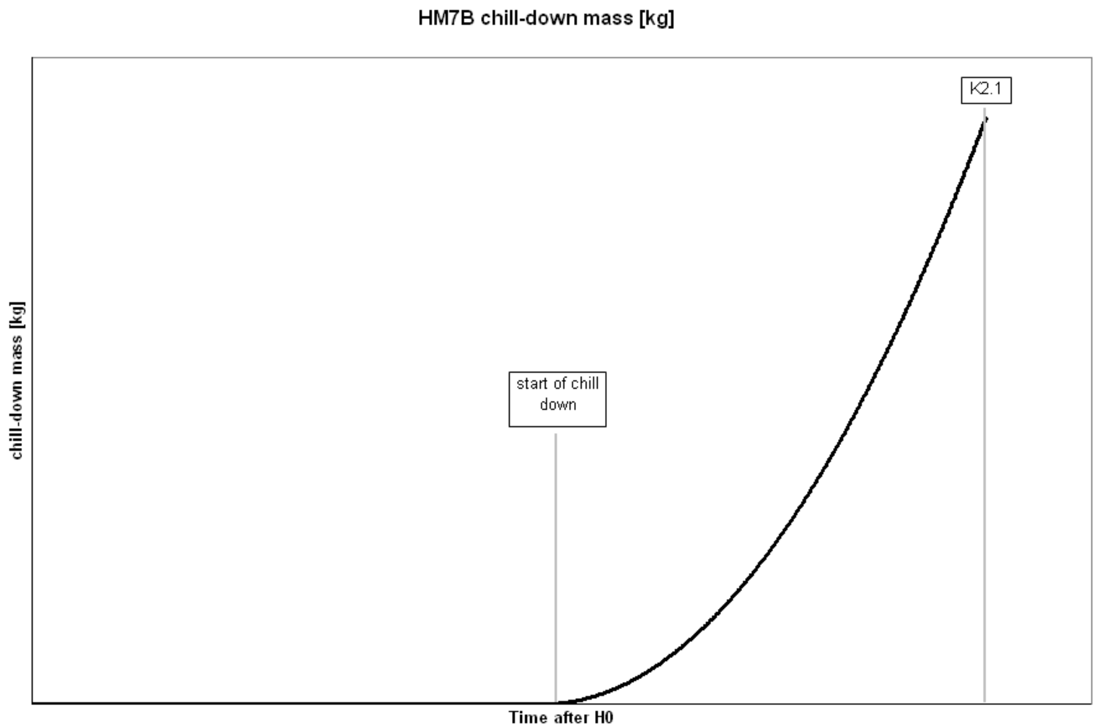


(b) Heat fluxes during flight.

Figure 3: Heat fluxes as an outcome from post flight analysis.



(a) Atmospheric pressure



(b) Chill-down mass

Figure 4: Pressure evolution of atmospheric pressure and engine chill-down mass during EPC lift-off and flight.

3. Stratification

Due to external heat fluxes into the LH_2 tank a convective flow appears and creates a hot layer near the surface and temperature evolution in LH_2, which is called stratification. When the saturation temperature is reached the liquid hydrogen evaporates and bubbles may occur. A small boundary layer of evaporated hydrogen is built over the liquid-vapor interface and cold liquid from the center of the tank flows to the wall and is also heated.

While draining (during the ESC-A flight) the temperature of the fluid and the steam pressure increase at the pumps and cavitation can occur. The collapse of these bubbles can damage the rotating parts of the pumps, which causes a mission failure. To avoid cavitation a thermal mass with the critical temperature will not be used for the mission. Therefore numerical analysis for ESC-A flight is performed with the commercial CFD software package ANSYS/FLUENT taking into account the associated physical effects.

3.1 Physical Effects

The Grashof number characterizes this convective flow considering the heat flux as temperature difference between wall and fluid. The Nukiyama curve illustrates this temperature difference for different heat fluxes. With these experimental data also the heat transfer coefficient can be calculated. Similarly the Rayleigh number describes the flow regime and points out a turbulent flow for this stratification model with $Ra > 10^{10}$. To proof the numerical results the convective flow velocity can be estimated by introducing an equivalent Reynolds number. The numerical analysis shows good conformity with the analytical prediction.

For small heat fluxes convective flow is dominant. With rising heat input bubbly flow occurs and increases the heat transfer into the liquid. Sensitivity analysis have revealed the accuracy of the standard wall function to calculate heat transfer for bubbly flows. With the properties of liquid hydrogen bubble diameter, frequency and nucleation side density the bubbles rise with a spheric shape and form a primary trail. I.e. caused by the relative velocity of the rising bubbles a small amount of liquid is trailed behind the bubbles and influences the velocity in the boundary layer. Analytical analyses have shown that the influence on the convective flow for the ESC-A LH_2-tank is negligible what simplifies the numeric analysis because the gas bubbles need not to be modeled.

If the liquid exceeds the saturation temperature vaporization will occur. With neglected overheating the temperature is limited to saturation by implementing the heat flux:

$$\dot{q}_{evap} = \frac{\int_{T_{sat}}^{T} c_p \rho_l \, dT}{dt}. \tag{4}$$

3.2 Numerical model

To simulate stratification the commercial computational fluid dynamics (CFD) software package ANSYS/FLUENT 12.0 is used. With user-defined-functions (UDF) the standard functionality of Fluent is extended by makros in C-code.

The thermodynamic model is built with an axisymmetric geometry to analyze the LH_2 tank with liquid and gas phase including the structure and insulation materials considering heat conduction and heat capacity (see Figure 5). To implement convective, radiative and aerothermal heat fluxes the walls are divided in several zones. An equidistant mesh with 138,000 cells is build and proved by a mesh sensitivity analyses. Pressure inlet and massflow outlet have the correct position and flow area but tank internal structures and lines can not be modeled.

Beginning after topping up the ground phase and all flight phases are simulated. Therefore pressurization, draining, acceleration and heat fluxes are considered.

To implement the draining phase a volume of fluid (VoF) model is chosen. With an additional continuity equation the volume fraction of different, not inter-penetrating phases and the material properties are calculated:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla(\alpha_q \rho_q \vec{v}_q) = \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})\right], \tag{5}$$

$$\rho = \alpha_2 \rho_2 + (1 - \alpha_2)\rho_1. \tag{6}$$

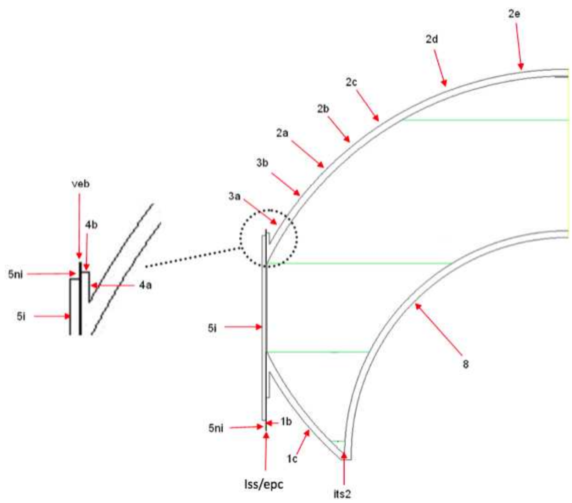


Figure 5: Geometry and heat flux zones of the LH_2 tank.

These material properties are considered in the energy and momentum equation, which can result numerical inaccuracies for the heat transfer at the phase interface. To avoid this effect the turbulence parameter C_μ of the k-ϵ-turbulence model is corrected per UDF, which can be confirmed by an analytical estimation regarding the Froude number [1]:

$$C_\mu = 0.125 Fr_{turb}^2 + 0.014 Fr_k \tag{7}$$

with $Fr_{turb} < 0.35$.

Regarded in the energy equation the high heat transfer at the phase can be avoided. The impact on the momentum equation, which shows a minimal higher convective flow velocity, is negligible.

Numerical and analytical sensitivity analyses have shown that the limitation of the liquid phase to saturation temperature has to be regarded by equation (4) as heat sink in the energy equation considering vapor and hydrostatic pressure. No condensation in the vapor phase and no mass transfer due to vaporization are modeled.

All material properties of the liquid, structure and insulation are temperature-dependent whereby the convective buoyancy is implemented. Also the time-dependent penetration of helium into the open cell insulation is regarded which has a significant impact on thermal conductivity and heat capacity of the insulation.

The environment is defined by one and two dimensional arrays per UDF in language C. While draining rate, pressure and acceleration are only time-dependent the heat transfer coefficient is calculated by time and wall temperature.

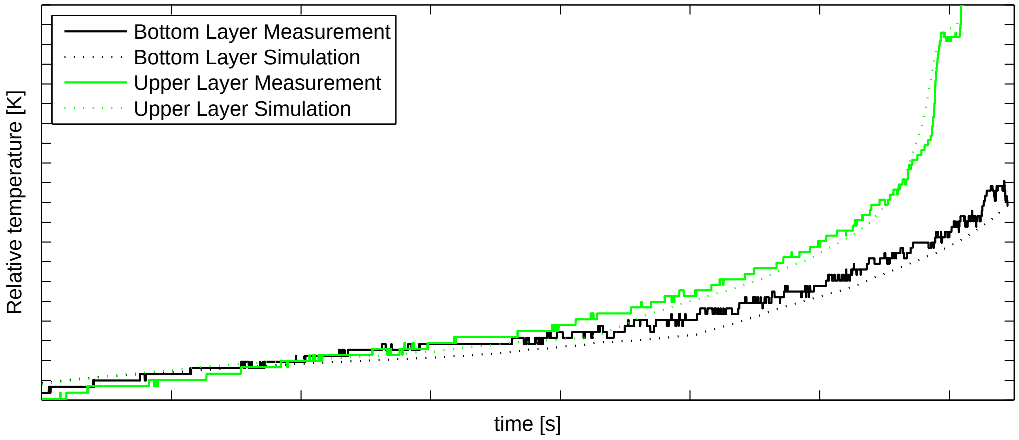
3.3 Numerical Results and correlation with flight data

The numerical analyses starts after pressurization and examine all liquid temperature sensors. It becomes apparent that the lower liquid layers at tank bottom are calculated too cold whereas the higher temperature sensors near the phase interface correlate very well (Figure 6).

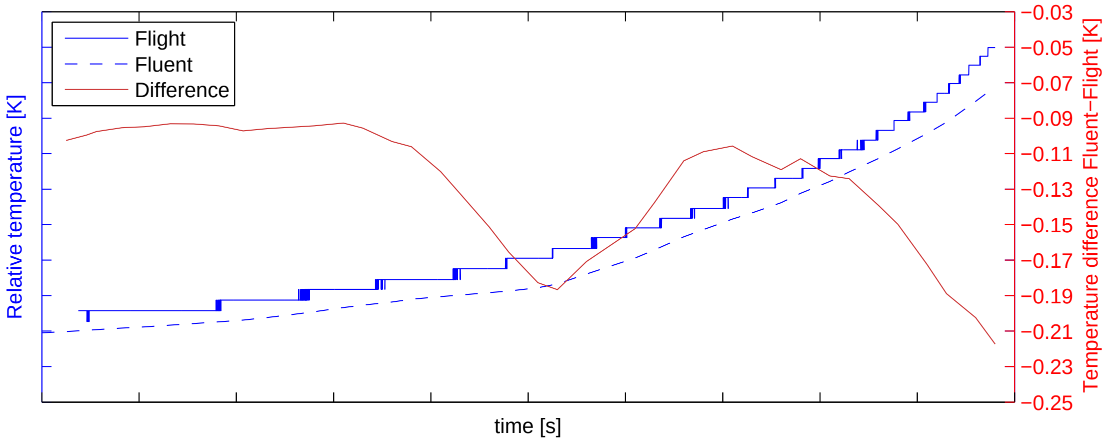
All temperature sensors in Fluent show a cold liquid layer which moves in outlet direction. The cold bottom layer can be find in the temperature evolution at the turbopump inlet while draining phase in Figure 6. At the beginning of draining the calculated temperature at the turbopump inlet is 0.1 K too cold and the mean temperature difference of the whole draining phase has a value of -0.13 K.

The correlation with flight data has shown that the environment is insufficient defined in respect of stratification. In comparison with temperature measurements at the structure thermal inputs are undervalued. Furthermore the heat flux of the hot pressurization line can not be regarded in an axisymmetric model. The chilldown process and its release of energy is very complex and not examined in this model. A modified turbulence model also has an impact on thermal conductivity an has to be analyzed. All these inaccuracies and limitations can explain the temperature offset at the turbopump inlet.

Nevertheless it is shown that the numerical analysis of stratification including draining is possible. The accuracy of the performed reference case is not conservative but sufficient for a first estimation of the stratification profile at the turbopump inlet. In addition with the simulation of cold and hot case the analysis can be validated to estimate the stratification profile of future launchers.



(a) Bottom and Upper temperature sensors



(b) Temperature at turbopump inlet

Figure 6: Temperature evolution during draining phase.

4. Conclusion

Two tools were developed and validated with flight data to analyse the behavior of liquid hydrogen inside the tank taking into account physical effects and changing conditions. These tools can be used for forecast studies and post flight analysis for ground, EPS flight and ESC-A flight phase.

References

[1] Venayagamoorthy, S. K.., J. R. Koseff, J. H. Ferziger, L. H. Shih. 2003. Testing of RANS turbulence models for stratified flows based on DNS data. Center for Turbulence Research.