

A fast engineering tool for simulation and design of propellant management systems in liquid propelled launcher stages

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At the Space Launcher System Analysis (SART) department of DLR, an engineering tool for the simulation of propellant management systems is under development. The tool is called PMP (Propellant Management Program). This paper will describe the tool and some of the models the tool uses. Some models have been adapted or added and some will be implemented in the future. The paper will also describe the results of a test case compared to the EADS Astrium tool EUCES.

1. Introduction

A well designed propellant management system in rocket stages is of crucial importance for successful launcher design. The propellant management system can be optimized such that propellant residuals and loaded propellant are minimized. This is especially important in upper stages, where each kilogram saved can be directly added to the payload. To obtain an efficient design, it is necessary to be able to simulate propellant behaviour and propellant management systems using fast engineering methods (CPU time in order of seconds, maximum a few minutes). This way propellant management can be integrated in the preliminary design phase where different propellant management systems can be compared and a trade-off can be made. Within the German national program "cooperation project upper stage", the SART (Space Launcher Systems Analysis) department at DLR in Bremen is developing a tool for this purpose. The tool is called PMP (Propellant Management Program)

The main task of the propellant management system is to make sure that propellant enters the engine under the right conditions. Typically about 90% of the launcher takeoff mass consists of propellant. The most obvious way to minimize propellant mass is probably to increase the specific impulse of the engine. But engine performance cannot be increased indefinitely. In fact current rocket engine technology is reaching its limits. It is therefore important to optimize the propellant management system to minimize propellant losses (for example residual propellant and propellant boil off).

In its current form the tool PMP calculates amongst others the required pressurization gas mass, pressure losses throughout the propellant feed system, pressure at all locations, and it includes a simple method for the determination of evaporated propellant mass and self-pressurization. Visualization of the propellant management system is also possible (Figure 1). For the future some extensions and improvements are foreseen. For example a more detailed model for evaporation of the liquid and stratification of liquid and gas is to be implemented. Also a model for propellant slosh is foreseen. Propellant slosh can create undesired forces which have to be counteracted by the attitude control system, and it can also lead to undesired thermodynamic effects like strong pressure drops.

An example of an upper stage propellant management simulation will be presented and compared to EUCES, a tool used at Astrium based on EcosimPro.

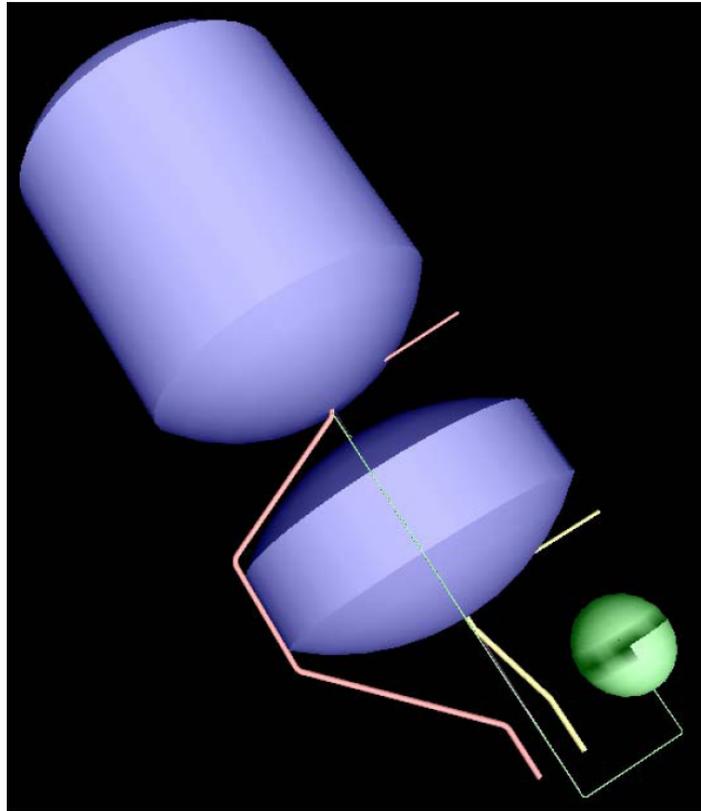


Figure 1. Visualization of Upper Stage Propellant Management System as Automatically Generated by PMP

2. Logic of the program

The goal of PMP is to quickly simulate a propellant management system (CPU time in the order of seconds, maximum a few minutes). The tool is not intended for detailed simulation of every phenomenon, but rather it should be able to give an estimation of integral values.

The input data of PMP consists of two parts; a mission specific part and a propellant system specific part. For the mission specific part the user has to specify the mission duration and the desired tank pressure. In addition the user may specify liquid outflow (propellant mass flow), acceleration, external temperatures and radiative heat flux. The mission specific input can be defined as a function of time. The propellant system specific input consists of for example wall thickness, materials, propellant mass, initial propellant temperature and tank geometry. It is not a function of time. After providing the input PMP is able to calculate the following data:

- pressure (including hydrostatic pressure)
- pipeline pressure drops
- required pressurization mass
- masses of all components
- temperatures of the ullage and liquid
- propellant loss (evaporation, venting)
- Net Positive Suction Pressure (NPSP)

During the simulation, pressure in the tanks will start to vary because of tank drainage and propellant boil off. PMP adapts the pressurization gas mass flow such that the desired pressure in the tank is reached. If the pressure in the tank exceeds a maximum, gas is vented until the desired pressure is reached.

Using tank pressure, hydrostatic pressure, pipeline radius, material properties and pipeline geometry (length and bends) velocity and pressure at each location in the pipeline can be calculated. Using the pressure at the feedline exit (engine inlet), the Net Positive Suction Pressure (NPSP) is calculated. The NPSP is very important parameter in Propellant Management System design. If it is too low, cavitation may take place in the turbopump which can lead to catastrophic failures.

3. Phase change models

A major improvement in PMP has been made on the fluid temperature and phase change models. The old model assumed the liquid temperature to be homogenous and constant. The assumption was that heat flowing into the liquid is used to evaporate a certain amount of this liquid. The amount of liquid evaporated was calculated by dividing the heat flow into the liquid by the energy required to heat up the liquid to the boiling temperature plus the heat of evaporation plus the energy required to heat up the evaporated liquid to the ullage gas temperature. Temperature of the liquid was assumed to remain unchanged:

$$\dot{m}_{vap} = \frac{\dot{Q}_{liq}}{c_{p liq} (T_{sat} - T_{liq}) + h_{vap} + c_{p gas} (T_{gas} - T_{sat})} \quad (1)$$

Where

\dot{m}_{vap}	is the evaporated liquid mass	[kg/s]
\dot{Q}_{liq}	is the heat flow into the liquid	[J/s]
$c_{p liq}$	is the specific heat at constant pressure for the liquid	[J/kg/K]
$c_{p gas}$	is the specific heat at constant pressure for the gas	[J/kg/K]
T_{sat}	is the saturation temperature	[K]
T_{liq}	is the liquid temperature	[K]
T_{gas}	is the temperature of the gas	[K]
h_{vap}	is the heat of vaporization	[J/kg]

Apart from the fact that liquid temperature was assumed constant, the model has some additional shortcomings and therefore was adapted. In reality, some liquid can evaporate even without energy inputs from the surroundings. According to the evaporation model based on kinetic theory [1] [2], the evaporated mass is a function of the saturation pressure of the liquid and the partial vapour pressure in the ullage.

$$\dot{m}_{vap} = \sigma A \sqrt{\frac{M}{2\pi RT}} (P_l^{sat} - P_v) \quad (2)$$

Where:

\dot{m}_{vap}	is the evaporated liquid mass	[kg/s]
σ	is the accommodation coefficient	[-]
A	is the liquid-gas interface surface area	[m ²]
M	is the molecular mass	[kg/mol]
R	is the universal gas constant	[8314.4 J/kg/mol/K]
T	is the temperature at the liquid–vapour interface	[K]
P_l^{sat}	is the liquid saturation pressure	[Pa]
P_v	is the vapour pressure (or partial pressure of the liquid vapour in case of gas mixture)	[Pa]

As long as there is a positive pressure difference, liquid will evaporate even if there is no energy input from the surroundings. In this case energy will be extracted from the liquid and the liquid temperature will drop. If the liquid saturation pressure drops below the partial pressure in the gas (the pressure difference is negative), gas will start to condensate.

The liquid temperature can be calculated by determining the net heat input into the liquid. To obtain the net heat input, the heat required for evaporation of the liquid mass determined with equation (2) is subtracted from the heat input into the liquid from the surroundings.

The problem when using this model is the determination of the accommodation coefficient. This coefficient is a measure for that chance of a molecule to undergo a phase change. The accommodation coefficient can obtain values between 0 (no phase change) and 1 (maximum evaporation rate). Values for this accommodation coefficient are hard to obtain and values indicated in literature tend to vary over a large range.

The kinetic theory may not be valid for all fluids. In such cases, the accommodation coefficient can be a 'tuning' parameter to adapt the numerical results to that of measured results, rather than a real 'physical' parameter. For these cases, limiting the accommodation coefficient between 0 and 1 makes no physical sense anymore.

4. Example

PMP including the new phase change model was compared to the EADS Astrium tool EUCES. Like PMP, EUCES is a propellant management tool which calculated propellant conditions in tanks and pipelines [3] [4]. However, the goals of each tool are somewhat different. Whereas PMP is meant to quickly determine the integral values of the propellant management system, EUCES simulates the processes on a more detailed level.

EUCES has been extensively tested. It is therefore interesting to compare PMP with EUCES. A simple, adiabatic tank model without any heat transfer between propellant and tank wall but including propellant outflow has been set up. The tank is pressurised using helium as a pressurant. Using this simplified model, some basic things such as evaporated propellant mass, pressurisation gas mass, ullage temperature and heat transfer between liquid and ullage could be compared.

The test case concerns a model of the upper stage LOX tank of the WOTAN K3 launcher design. The WOTAN launcher has been jointly designed by EADS Astrium and DLR-SART [5]. The input data for the test case can be found in Table 1. In Figure 2 it can be seen that the upper stage tanks as modelled in PMP are not an exact representation of the actual design. For example the cylindrical sections in the middle of the tanks are a bit higher in the PMP representation. This is explained by the fact that PMP can only model cylinders and spherical segments, but the actual tank domes are not spherical segments. However, this is usually a very good approximation of the tank shape.

LOX mass [kg]	28330
LOX mass flow [kg/s]	34.2
Burn time [s]	802
LOX tank press [bar]	3
LOX initial temperature [k]	90.5
Helium pressurant initial temperature [K]	270
Helium pressurant initial storage pressure [bar]	393
Heat transfer coefficient between ullage and liquid [W/m ² K]	5

Table 1. LOX Tank Data

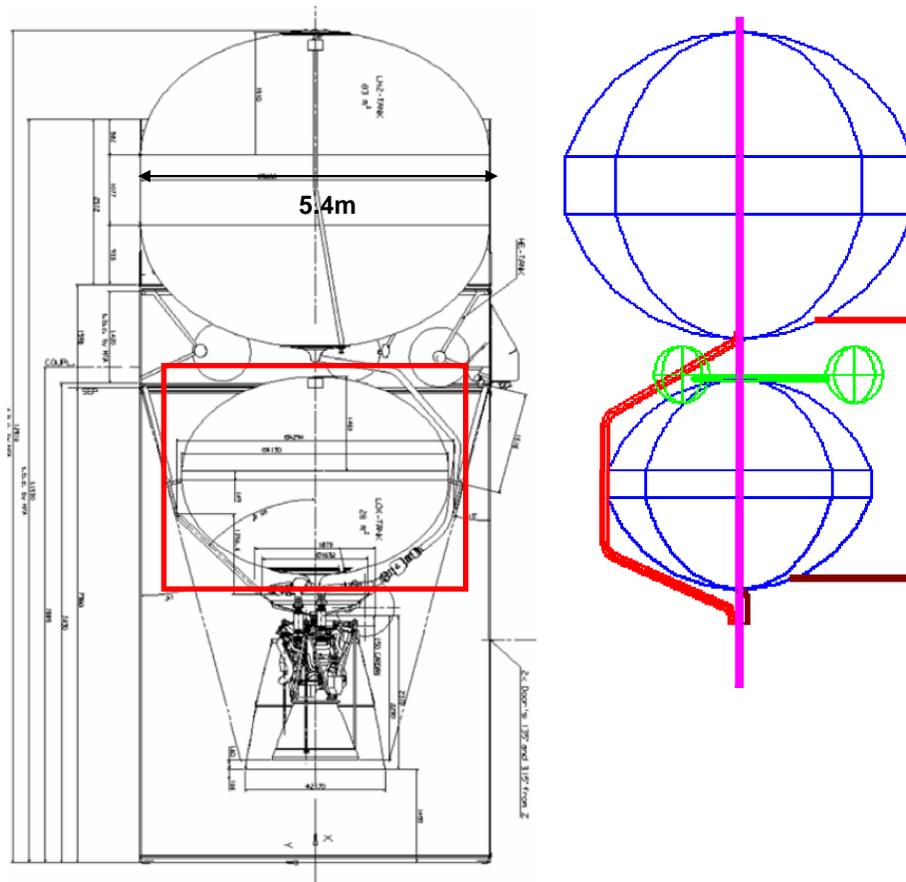


Figure 2. The WOTAN K3 Upper Stage, with the LOX Tank Marked by a Red Square. The PMP model with the approximated geometry is shown on the right.

Figure 3 shows the heat transfer between liquid and ullage. The negative numbers mean heat is transferred from the ullage to the liquid. The heat transfer coefficient between liquid and ullage has been set to equal values for both cases (see Table 1). However, a difference in heat transfer can still be seen. This can be explained by the fact that when using PMP, the tank geometry is approximated. Heat transfer between the liquid and ullage is a function of the heat transfer coefficient, the liquid surface area and the temperature difference between liquid and ullage. As the tank is drained, the liquid surface area changes. Because tank geometries for both cases differ slightly, the liquid surface area will also differ and therefore there is a difference in heat transfer.

The simulation begins at about $t=220$ s, after first stage separation. At this time the tank is almost completely filled. The liquid surface area is small and the heat transfer low. At about $t=620$ s, the tank is filled half way. Here the tank radius is the largest and the liquid surface area has reached a maximum. Therefore the heat transfer has also reached its maximum value.

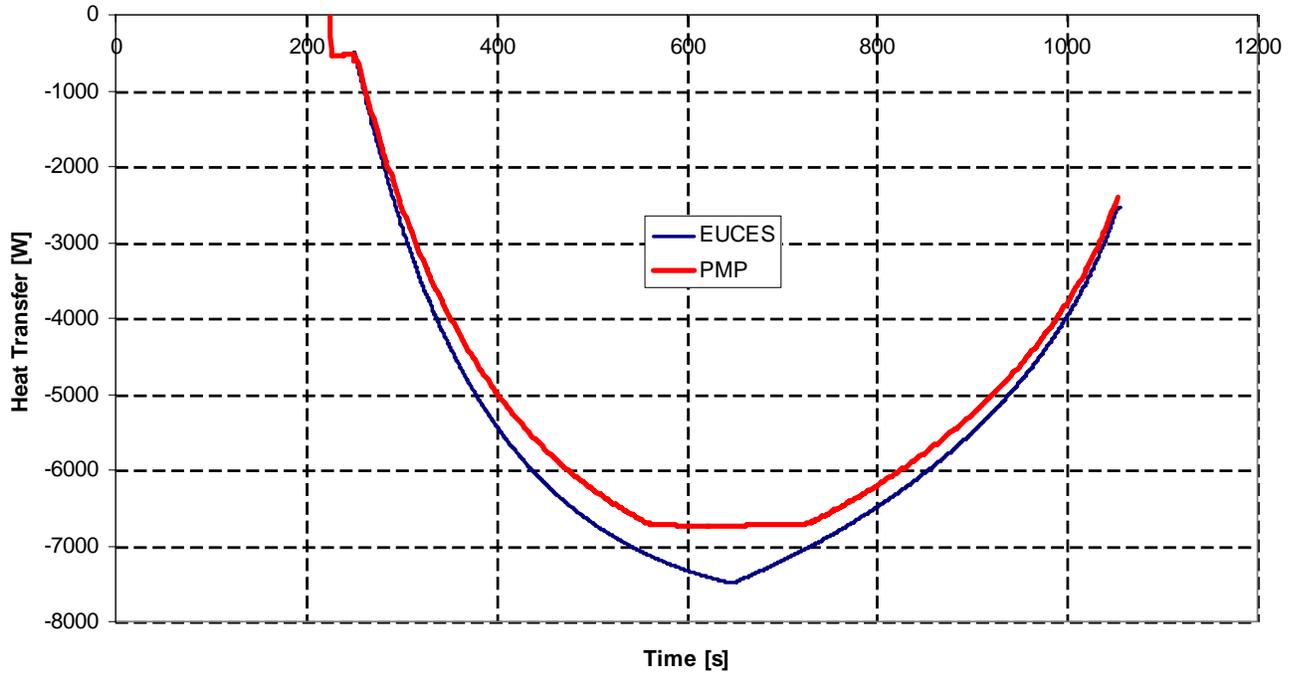


Figure 3. Heat Transfer Between Liquid and Ullage

Figure 4 shows the evaporated propellant mass. The evaporation model in PMP requires the input of the accommodation coefficient. Data on accommodation coefficients for oxygen are hard to obtain. The coefficient has been chosen such that the evaporated mass equals the evaporated mass in EUCES. This results in a very small accommodation coefficient of $1 \cdot 10^{-6}$.

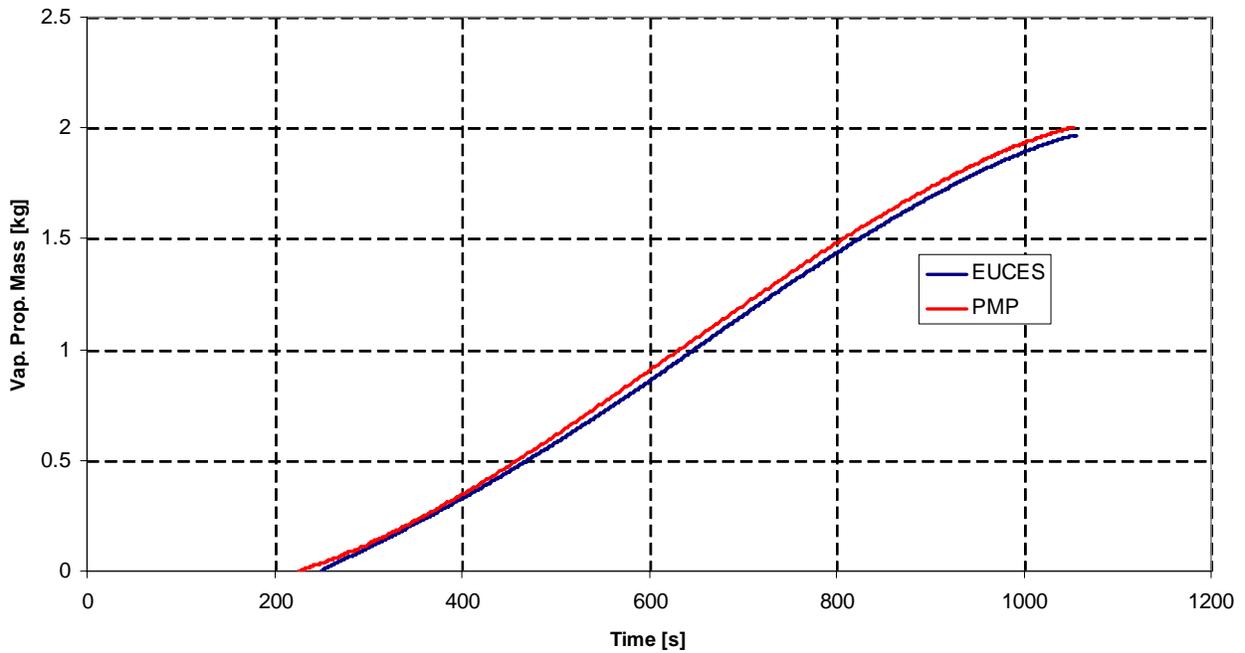


Figure 4. Evaporated Liquid Mass

The development of the ullage temperature is shown in Figure 5. The PMP simulation results in a somewhat lower ullage temperature, which seems a bit strange because according to Figure 3 the heat transferred from the ullage into the liquid is less in case of PMP. Therefore one would expect the ullage temperature to be higher.

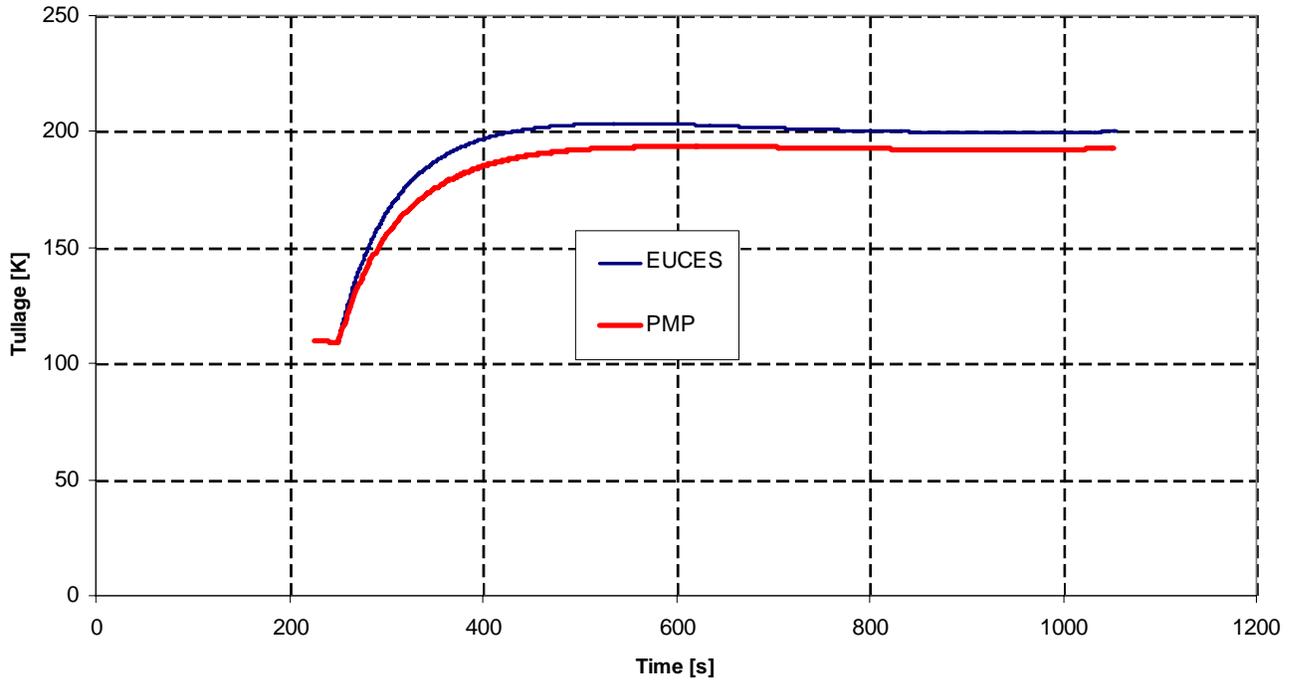


Figure 5. Ullage Temperature Evolution

Pressurisation gas mass (Helium) is higher for the PMP case, as can be seen in Figure 6. A lower ullage temperature will lead to a lower pressure and therefore the pressurisation gas mass must be higher to maintain the desired tank pressure.

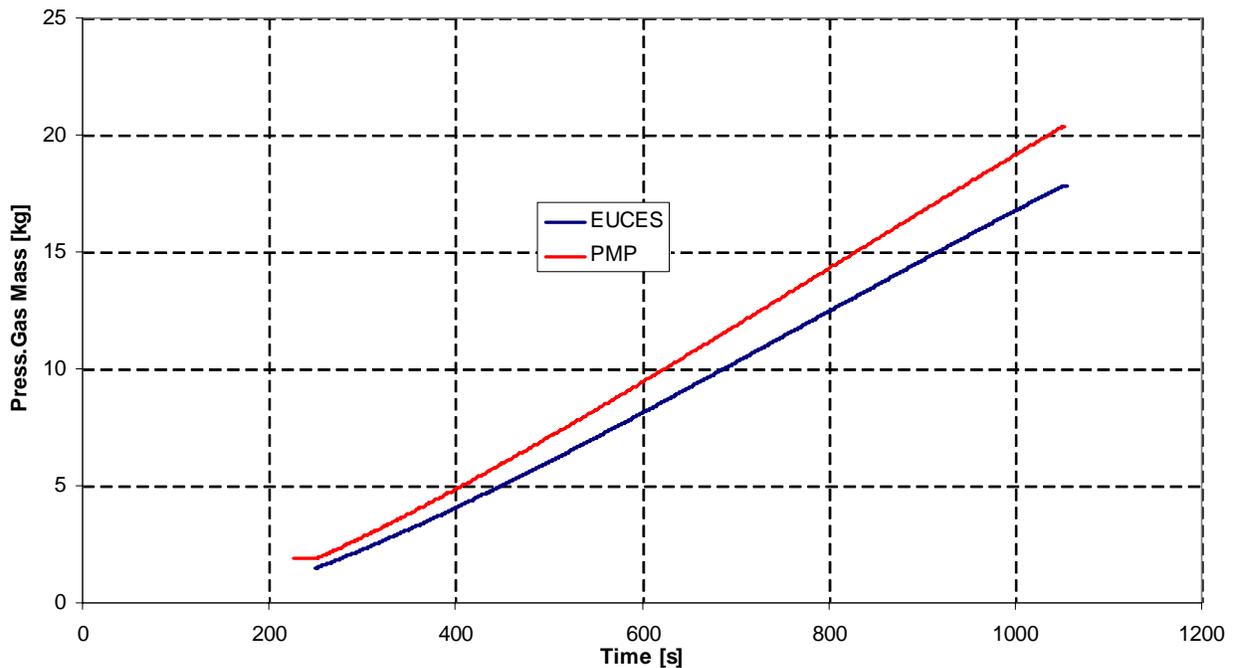


Figure 6. Pressurisation Gas Mass

5. Thermal stratification in the liquid

Thermal stratification in the liquid is important because a change in the liquid temperature also means a change in the NPSP. If the liquid temperature is too high, NPSP can drop below critical values and cavitation can take place in the turbopumps.

Stratification of the liquid can also have a negative side effect when propellant sloshing occurs. Propellant sloshing is not yet implemented in PMP. Propellant sloshing dynamics leads to undesired mechanical loads and can also lead undesired thermodynamic effects, such as strong pressure drops due to the mixing of thermal layers in the liquid. The dynamics of sloshing and its mechanical loads are well understood and analytical relations exist. Implementing these into the program should be fairly straightforward. The thermodynamic aspect of sloshing is a more difficult subject. Currently, experiments are carried out by the Centre of Applied Spaceflight and Microgravity (ZARM) in Bremen to investigate the latter. Simplified models are extracted from these experiments and from numerical analysis with 3D flow solvers such as the commercially available code FLOW 3D [2]. It is foreseen to implement these in PMP.

Thermal stratification in the liquid can be modelled by assuming that the tank is cylindrical and the heat input through the tank domes is negligible. This way, a boundary layer model can be set up and by integrating the liquid mass flow in the natural convection boundary layer along a heated tank wall, an estimation for thermal stratification can be obtained. Additional assumptions are:

- That the initial temperature of the liquid is uniform
- That all of the heat input into the tank wall appears as sensible heat in the boundary layer
- That all of the flow in this boundary layer goes into a heated upper stratum
- That the lower stratum remains at initial (bulk) temperature
- That there is no mixing between the upper and lower stratum

and following the procedure in [6] it is possible to compute a heated volume (volume of the upper stratum) and an average temperature of this heated volume. A schematic representation of the model is given in Figure 7. Here, T_b is the initial (bulk) temperature and T_s is the liquid surface temperature. The average temperature of the heated volume will be somewhere between T_b and T_s , depending on the temperature profile in the heated volume.

The increase in heated volume can be determined using:

$$\dot{V}_H = \left(A_H - \frac{V_H - \dot{V} t_{of}}{A_c} 2\pi R \right) \frac{h}{\rho_l c_{p_{liq}} \xi} \quad (3)$$

Where

\dot{V}_H	volumetric increase of the upper stratum	[m ³ /s]
A_H	tank wall heated area	[m ²]
V_H	volume of the upper stratum	[m ³]
\dot{V}	volumetric outflow rate	[m ³ /s]
A_c	area of liquid surface	[m ²]
t_{of}	time after start of the liquid outflow	[s]
R	tank radius	[m]
h	wall-boundary layer heat transfer coefficient	[W/m ² /K]
ρ_l	density of liquid	[kg/m ³]
ξ	factor depending on temperature and velocity distributions in the boundary layer [-]	

The average temperature in the heated upper stratum can be calculated using the following relation:

$$\dot{T}_{av} = \frac{1}{V_H \rho_l c_{p\text{liq}}} \left(A_H - \frac{\dot{V} t_{of} 2\pi R}{A_c} \right) \dot{q} \quad (4)$$

with

- \dot{T}_{av} the rate of increase of the average temperature in the upper stratum [°/s]
- V_H the volume of the upper stratum [m³]
- \dot{q} heat flux rate [W/m²]

By assuming a linear temperature profile in the upper stratum the temperature at the liquid surface can be calculated from T_b (bulk temperature) and T_{av} (the average temperature in the upper stratum). As soon as the temperature at the liquid surface reaches the saturation temperature, the evaporation process is called 'natural convection boiling'. Once the liquid surface temperature is known, the evaporation rate can be calculated using (2). Results of this simplified model will be compared with results using FLOW 3D. Figure 8 shows the results obtained by a FLOW 3D simulation of an experiment conducted at ZARM using liquid nitrogen (LN2) as a fluid. The figure shows that part of the test-tank filled with LN2. In this figure the heated boundary layer which transports the warm liquid into the upper stratum can clearly be seen, justifying some of the assumptions made in the model described above. In the future, also simulations of real launch vehicle tanks will be made using FLOW 3D.

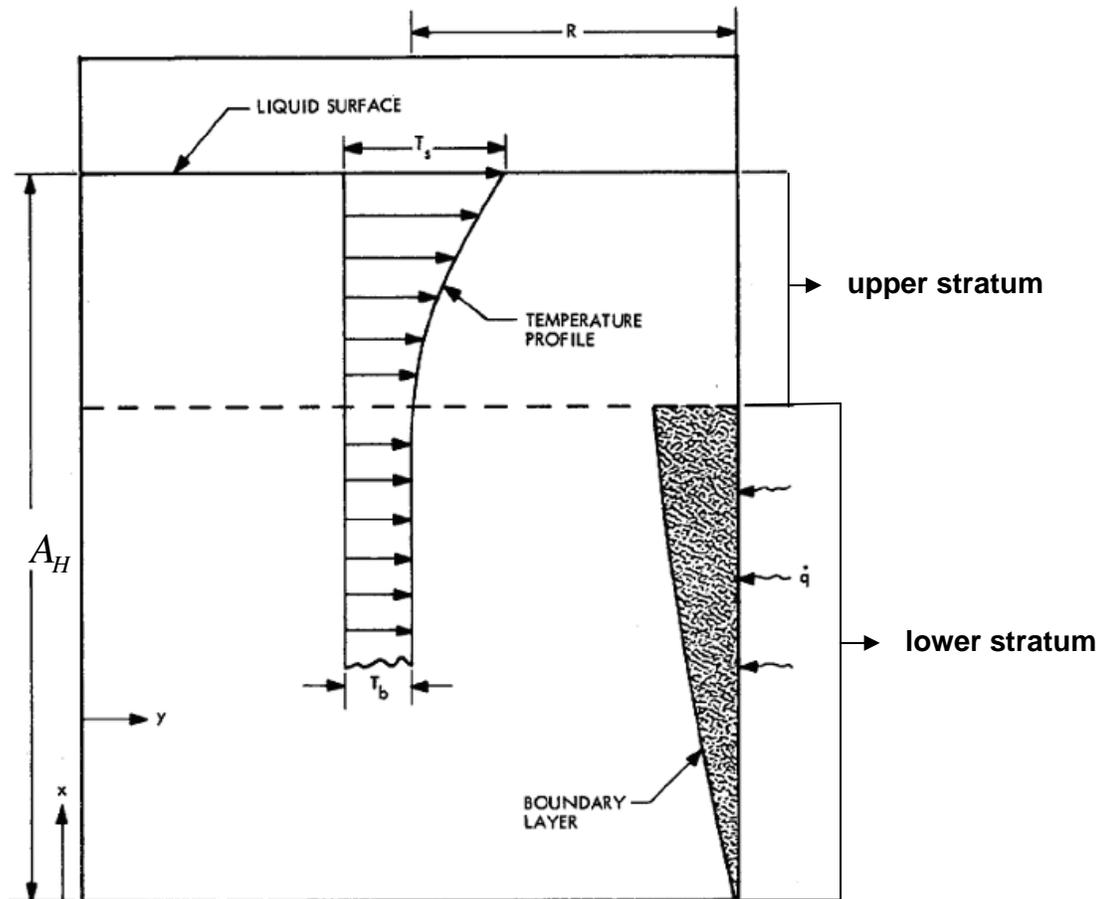


Figure 7. Stratification Model [7]

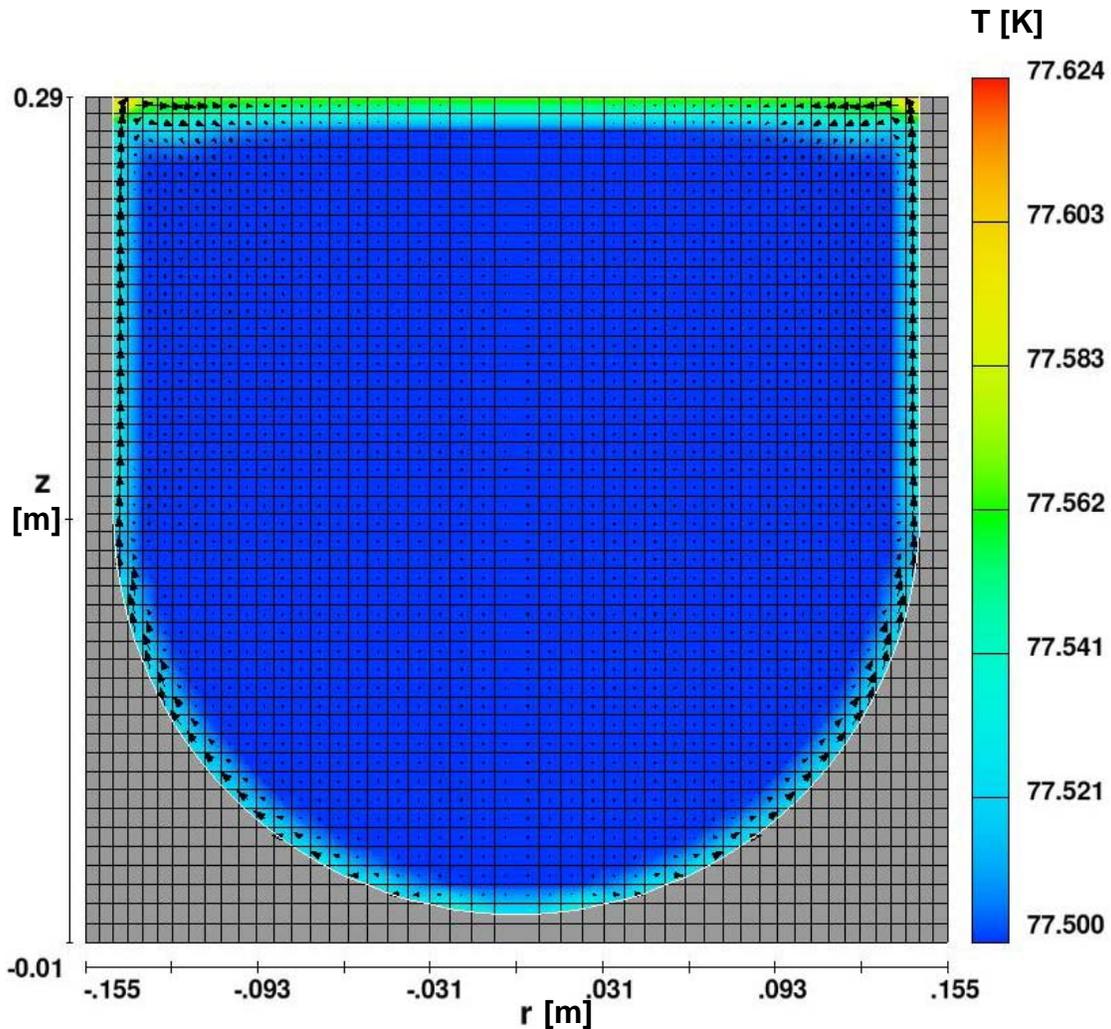


Figure 8. FLOW 3D Model of Stratification Process of Test at ZARM

6. Future work

The stratification model in its current form is limited to tanks heated through the cylindrical part only. This can be a good approximation when the tank is largely cylindrical and the dome surfaces are small compared to the cylindrical surface. This is the case in for example first stage tanks. Additionally, a large part of the volume in the upper dome will be occupied by the ullage. In such a case the assumption that no heat will enter the liquid via the upper dome is a valid one.

In application where the dome surface is large compared to the cylindrical surface, heating through the domes cannot be neglected. This is often the case for upper stage tanks. The WOTAN LOX tank illustrates this very well. The cylindrical part of this tank is almost zero and thus the heating of the liquid takes place only through the domes. This is clearly an example of a tank where the stratification model in its current form does not apply. A part of the future work will therefore be the adaptation of the model such that it can also be used for upper stage tanks.

Another important part of the future work will be the implementation of a sloshing model. The sloshing model will not only determine the forces on the stages, but it will also include a model for the estimation of the pressure drop encountered during cryogenic sloshing. The stratification and slosh model will be developed by investigating the results of 3D numerical analysis using FLOW 3D, as well as investigating the results from experiments executed at ZARM.

7. Conclusions

PMP is able to simulate propellant management system very fast. Some models have adapted or added to increase its accuracy. For example the phase change model has been improved and a stratification model has been added. PMP shows good agreement with the Astrium tool EUCES for a simple adiabatic test case, although a slight difference in ullage temperature is present. The stratification model is based on a boundary layer transport model, which has been shown to be plausible by comparing it with the results from a FLOW 3D simulation.

8. References

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