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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 simulating propellant management systems is under development. The tool is called PMP (Propellant Management Program). This paper describes 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 also describes the results of a test case in comparison with the EADS Astrium EUCES tool.

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 for upper stages where each kilogram saved can be directly added to the payload. To obtain an efficient design, fast engineering methods (CPU time on the order of seconds, maximum a few minutes) are required to simulate propellant behavior and propellant management systems. 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 department of 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

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minimize propellant mass is probably to increase the specific impulse of the engine. But engine performance cannot be increased infinitely. In fact, current rocket engine technology reaches its limits. It is, therefore, important to optimize the propellant management system to minimize propellant losses (for example, residual propellant and propellant boiloff).

In its current form, the PMP tool calculates amongst others the required pressurization gas mass, pressure losses throughout the propellant feed system, pressure at all locations, and includes a simple method for determining evaporated propellant mass and self-pressurization. Visualization of the propellant management system is also possible (Fig. 1). For the future, some extensions and improvements are foreseen. For example, a more detailed model for liquid evaporation and liquid–gas stratification 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. It can also lead to undesired thermodynamic effects like strong pressure drops. Below, the example of an upper stage propellant management simulation is presented and compared to EUCES, a tool based on EcosimPro and used at Astrium.

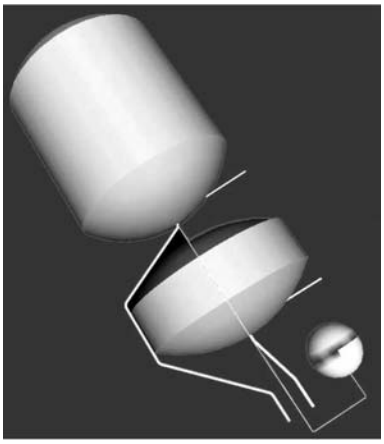

Figure 1 Visualization of upper stage propellant management system as automatically generated by PMP

2 LOGIC OF THE PROGRAM

The goal of PMP is to quickly simulate a propellant management system. The tool is not intended for detailed simulation of each physical phenomenon, but rather it should be capable of providing 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, for example, of wall thickness, materials, propellant mass, initial propellant temperature, and tank geometry. This input is not a function of time. After providing the input, the PMP is capable of calculating the following data: pressure (includ-

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

During the simulation, the pressure in the tanks will start to vary because of tank drainage and propellant boiloff. Propellant Management Program 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), the velocity and pressure at each location in the pipeline can be calculated. Using the pressure at the feedline exit (engine inlet), the NPSP is calculated. The NPSP is a 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 for the fluid temperature and phase change models. The old model assumed the liquid temperature to be homogenous and constant. It was also assumed that the heat flux to the liquid was consumed to evaporate a certain amount of liquid. The amount of liquid evaporated was calculated by dividing the heat flux 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. The liquid temperature was assumed to remain unchanged:

$$\dot{m}_{\mathrm{vap}} = \frac{\dot{Q}_{\mathrm{liq}}}{c_{p_{\mathrm{liq}}} \left(T_{\mathrm{sat}} - T_{\mathrm{liq}}\right) + h_{\mathrm{vap}} + c_{p_{\mathrm{gas}}} \left(T_{\mathrm{gas}} - T_{\mathrm{sat}}\right)}$$

where $\dot{m}_{\mathrm{vap}}$ is the evaporated liquid mass, kg/s; $\dot{Q}_{\mathrm{liq}}$ is the heat flux to the liquid, J/s; $c_{p_{\mathrm{liq}}}$ is the specific heat at constant pressure for the liquid, J/kg/K; $c_{p_{\mathrm{gas}}}$ 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 gas temperature, K; and 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 vapor pressure in the ullage:

$$\dot{m}_{\text{vap}} = \sigma A \sqrt{\frac{M}{2\pi RT}} \left(P_l^{\text{sat}} - P_v \right) \tag{1}$$

where $\dot{m}_{\text{vap}}$ 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–vapor interface, K; P_l^{sat} is the liquid saturation pressure, Pa; and P_v is the vapor pressure (or partial pressure of the liquid vapor 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 vapor in the gas (the pressure difference is negative), the vapor 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 by Eq. (1) 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 the chance for a molecule to undergo phase change. The accommodation coefficient can vary from the values 0 (no phase change) to 1 (maximum evaporation rate). Values for this accommodation coefficient are hard to obtain and the values indicated in the 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 the measured data, rather than a real "physical" parameter. For these cases, limiting the accommodation coefficient between 0 and 1 makes no physical sense anymore.

4 EXAMPLE

Propellant Management Program including the new phase change model was compared to the EADS Astrium EUCES tool. Like PMP, EUCES is a propellant management tool which calculates propellant conditions in tanks and pipelines [3, 4]. However, the goals of each tool are somewhat different. Whereas the 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 pressurized using helium as a pressurant. Using this

Table 1 The LOx tank data

LOx mass, kg	28330
LOx mass flow, kg/s	34.2
Burn time, s	802
LOx tank pressure, 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, $W/(m^2K)$	5

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 are presented in Table 1. In Fig. 2, it can be seen that the upper stage tanks as modeled in the 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 the PMP can only model cylinders and spherical segments, but the actual tank domes are not the spherical segments. However, this is usually a very good approximation of the tank shape.

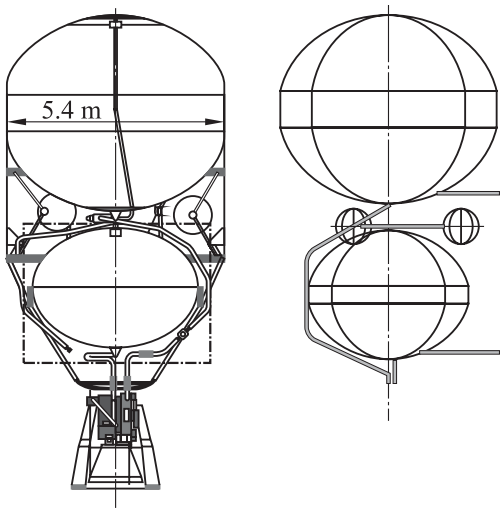

Figure 2 The WOTAN K3 upper stage, with the LOx tank marked by a dot-dashed square. The PMP model with the approximated geometry is shown on the right

Figure 3*a* 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 the PMP, the tank geometry is approximated. Heat transfer between the liquid and ullage is a function of the