THE ROLE OF DIFFERENT PARAMETERS IN THE PRESSURANT BUDGET OF VENUS EXPRESS AND ITS DYNAMIC EVOLUTION DURING THE MISSION

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ABSTRACT

An insufficient amount of pressurant gas in the propulsion system or a working temperature in the pressurant tank outside the qualification limits can cause a decrease in the performance of the thrusters or even the loss of the mission. This paper presents an engineering tool used able to compute the Pressurant budget of a mission and the effects of influencing parameters. The updated tool allows to also compute the temperature, pressure and mass evolution inside the pressurant tank during the various mission phases.
The tool has been used to verify the calculations done by Astrium Stevenage for Mars Express and Venus Express [1]. The pressurant gas used for both cases was helium. The tool permits to use other combinations of pressurant gases and propellants for different propellant systems (monopropellant and bipropellant systems).

NOMENCLATURE

NTO – Nitrogen Tetroxide
MMH – Monomethylhydrazine
UDMH – Unsymmetrical dimethylhydrazine.
Aerozine-50 – mixture 50:50 by weight of hydrazine and UDMH.
ACS – Attitude control system
RCS – Reaction control system

P_v – Vapour pressure, bar
S – Solubility, $kg_{Helium}/kg_{propellant}$
ρ - density, kg/m^3
m – mass, kg.
t - time, s.
P – Pressure, bar.
V – Volume, m^3.
Z – Compressibility.
R – Gas- law constant, $Pa \cdot m^3/mole \cdot K$
T – Temperature, K.
$\dot{q}$ – heat transfer, W.
U – Internal Energy, J.
h – convection heat transfer coefficient, W/m^2K.
A – if not specified, Surface of contact, m^2.

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1. INTRODUCTION

Monopropellant and bipropellant propulsion systems are normally pressurized with a Pressurant (normally Helium or Nitrogen). If the amount of Pressurant is not sufficient, the propulsion system will operate at too low pressures that affect the performance of the propulsion system and it can lead to the lost of the mission, therefore a control of the Pressurant budget for the mission must be done.
In the present paper, a tool has been developed to make pressurant analysis of the whole mission. This tool is able to perform pressurant analysis for monopropellant systems (Hydrazine) and bipropellant systems (MON-MMH, MON-UDMH and MON-Aerozine-50) using Helium or Nitrogen as a pressurant.
The tool returns values of the pressure and mass evolution inside the pressurant tank. At the same time the temperature evolution in the pressurant tank is also computed making two different approaches (semi-empiric approach and a experimental-based approach).

2. DEVELOPMENT OF THE STATIC AND THE DYNAMIC MODEL

A model was created on [2] in order to simulate the mass and the temperature evolution inside the pressurant tank during the mission. Two analysis were done:

- Static analysis
- Dynamic analysis

In the Static analysis, the Helium mass transferred to the propellant tank was analysed at every firing and in the dynamic analysis the temperature evolution along the mission was calculated.

2.1. Static Analysis

For the Static model, a mass balance was developed. The following features were taken into account:

- The evolution of the ullage volume in the propellant tank after every firing.

- The nominal ullage temperature. The partial pressure of Helium and the vapour pressure of the propellant in function of the temperature.
- The compressibility of the gas.
- Solubility of Helium in the propellant.
- Expansion of the liquid with the temperature.

Evaluation of the total mass of Helium in the system.

$$m_{TOTAL} = m_{Pressurant\ Tank} + m_{Lines} + m_{Fuel\ Tank} + m_{Oxidizer\ Tank} + m_{Dissolved\ in\ Fuel} + m_{Dissolved\ in\ Oxidizer} \quad (1)$$

The mass of Helium in the tanks and lines is computed with the modified gas law as follows:

$$m = \frac{P_{Helium} \cdot V}{Z \cdot R \cdot T} \quad (2)$$

The mass of Helium dissolved is computed by means of Henry's law in eq.3:

$$m_{Dissolved} = S \cdot P_{Helium} \cdot m_{propellant} \quad (3)$$

Dynamic effects were not analysed. In other words, the pressure in the pressurant tank drops during the firing, and thus the temperature also drops. As a consequence, the tank is overloaded with pressurant and when the setting temperature in the propellant tank is reached, the system is slightly over pressurised. The temperatures used to make these computations are specified in ch. 3.2. They correspond to the initial temperatures before the firing.

2.2. Dynamic Analysis

During the main mission phases, there is propellant consumption and Helium mass transfer from the pressurant Tank to the propellant tanks. Due to the mass transfer the pressure inside the pressurant tank drops, and therefore the temperature also drops. The dynamic analysis describes the temperature evolution during the firing.

Two estimations were used to compute the temperature evolution in the tanks.
- Experimental approach
- Semi-empiric approach

2.2.1. Experimental approach

The experimental approach is based on the model proposed in [2] explained eq. 9.

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}} \quad (4)$$

The temperature changes while the pressure is changing with a trend that depends on n (an experimental value). This value n depends strongly on the dimensions of the tank, the pressure and temperature conditions and the heat exchange (either by heaters or by radiation).
There is available data of Pressure and Temperature after and before the firing for MSG and Mars Express, therefore an n value can be obtained.
The design of the propulsion system of Mars Express and Venus Express is very similar; therefore the same coefficients were used. It must be noted that fair differences on n were found depending on the firing. Probably these differences are related with the fact that the firings were exposed at different conditions of radiation and the design characteristics of the propulsion system. However, the worst case was taken. This case corresponds to maximum temperature drops at equal pressure drop (n value is maximum). For Mars Express corresponds an n value of 1.072 and for MSG a value of 1.244.

2.2.2. Semi-empiric approach

A second semi-empiric approach was done because the final temperature estimations when the pressurant tank is close to empty were not realistic (the value of n didn't experience such a big temperature drop). The experimental approach already mentioned, is highly dependent on the dimensions, geometries, amount of pressurant and the materials used. Therefore at some changes on these parameters, the experimental might not give reliable results. The semi-empiric approach is based on an energy balance in the pressurant tank. The equation obtained is as follows:

$$m_{pressurant} \cdot \left.\frac{dU}{dt}\right|_{pressurant} = \dot{q}_{radiation} + \dot{q}_{heaters} + \dot{q}_{Tank} - \dot{m}_{transferred} \cdot Cp \cdot (T_{Helium}(t) - T_{ref}) \quad (5)$$

where q_{tank} is obtained as follows:

$$\dot{q}_{Tank} = m_{wall} \cdot \left.\frac{dU}{dt}\right|_{wall} = h_{convection} \cdot A \cdot (T_{wall}(t) - T_{Helium}(t)) \quad (6)$$

The parameters $h_{convection}$ and $q_{radiation}$ were not known or difficult to estimate, therefore they are based on experimental data obtained from telemetries of temperatures and Pressure evolution during a firing from Mars Express [9]. Different values were obtained from different firings; the worst case was taken that corresponds to a $q_{radiation}$ value of 26.9 W and $h_{convection}$ value of 35.1 W/m^{2}K.

Computation of the error of the temperature evolution

An error analysis was done. The computation was done by comparison of the best and the worst case experienced.
For the experimental approach, data for MSG and Mars Express was available whereas for the semi-empiric approach, there was found data for Mars Express.

3. CASES STUDIED

In order to test the tool, a review the role of the different parameters on the pressure and Temperature at the end of the mission and once the tanks of propellant are empty was done. The tool was applied for Venus Express mission.
Venus Express spacecraft has a bipropellant system composed of MON-1 and MMH.
Relevant to the Helium budget analysis, The mission is composed of a priming phase (where the pressurization of the system is performed) and four main mission phases (Cruise, capture, Apocentre lowering of the main engine and apocentre lowering 10 N, see ch. 3.2 for more details). In addition, an small amount of propellant has been used for the ACS/RCS.

3.1. Description of the system used.

The Venus Express spacecraft system is described in Fig. 1.

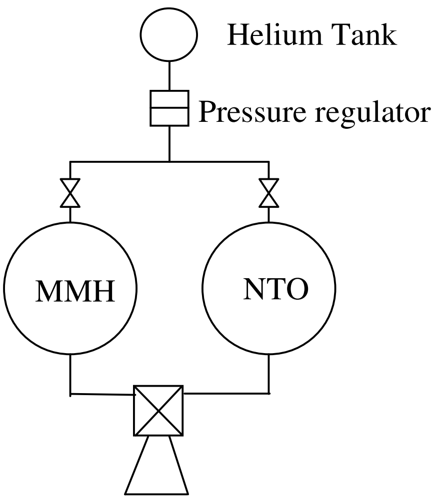

Fig. 1. Pressurant system studied.

Fig. 1 shows the main structure of the pressurant system simplified relevant to the computation of the Helium budget of the system.. The nominal case adopts the Primary pressure regulator by default (the working conditions are shown in Table 2).

Different input is needed in order to have a proper analysis of the system. The input and conditions used for this case are summarized in the section 3.2.

3.2. Initial conditions

Table 1 and Table 2 summarise the general conditions before the start of the burning.

Table 1. Conditions inside the tanks

	Pressurant Tank	Propellant Tanks
Pressure	275 bar	7 bar
Temperature	311 K	298 K
Volume	0.0376 m^3	0.2702 m^3

Table 2. General data

Other data of interest	
Mixture ratio	1.6499
Nominal propellant load	553 kg
Pressure regulator's Pressure	16.89 bar
Volume of the lines	0.0007 m^3

Table 3 summarises the conditions used for each mission phase.

Table 3. Conditions used during the mission phases

	Start	Priming	Mission phase			
			1	2	3	4
PC[a]	0	0	31.2	412.9	35.0	37.9
$T_{Pressurant}$	311	303 – 313 K				
T_{ullage}	298	287 – 300 K				
LoF[b]	0	0	3.8	51	4.3	4.7

[a]Propellant Consumption
[b]Lenght of Firings
The temperature is in K, the pressurant consumption in kg and the length of firings in min.

3.3. Cases of study

Different case studies at different conditions were performed. Firstly, analyses at different phases were done: at the end of the mission (after all mission phases) and once all propellant is depleted from the tanks.
Secondly, studies at different working conditions were made: at different propellant loads and at different temperatures in the ullage volume of the propellant tanks. The final output obtained is the final pressure and the temperature evolution during the mission in Pressurant tank

The cases studied are summarised in Table 4 and Table 5.

Table 4. Cases of study relevant to the end of the mission.

End of mission		Propellant Load (kg)				
		540	550	560	570	580
T_{ullage} (K)	287	✓	✓	✓	✓	✓
	293	✓	✓	✓	✓	✓
	298	✓	✓	✓	✓	✓
P(bar)	25	✓	✓	✓	✓	✓

In Table 4, the upper part of the table corresponds to the mass of propellant load used. On the left side of the table corresponds to the average temperature in the ullage volume during the whole mission. On the other hand, the pressure of 25 bars is referred to be the pressure at the end of the mission, for this case, the computation returns the average temperature of the whole mission.
The reason to set the pressure in pressurant tank at 25 bars is because it is the minimum inlet pressure to the pressure regulator that guarantees the outlet pressure remains within the tolerant band.

Table 5. Cases of study relevant to empty propellant tanks.

Empty tanks		Propellant Load (kg)				
		540	550	560	570	580
T_{ullage} (K)	287	✓	✓	✓	✓	✓
	293	✓	✓	✓	✓	✓
	298	✓	✓	✓	✓	✓
P(bar)	25	×	×	×	×	×

The information in Table 5 is displayed evenly than in Table 4, but it is referred to the final pressure once the pressurant tanks are empty. The computations at the final pressure of 25 bars were not done.

4. RESULTS OBTAINED

4.1. The nominal case

Fig. 2 shows the evolution of the pressure in the pressurant tank along the mission and Fig. 3 shows the temperature evolution in the pressurant tank during the mission. The results are presented in different figures and they correspond to a worst case. This case carries on a correspondence with a minimum expected temperature in the ullage volume (287 K) and a minimum temperature in the pressurant tank (303 K). The rest of the conditions used are explained in ch. 3.2.

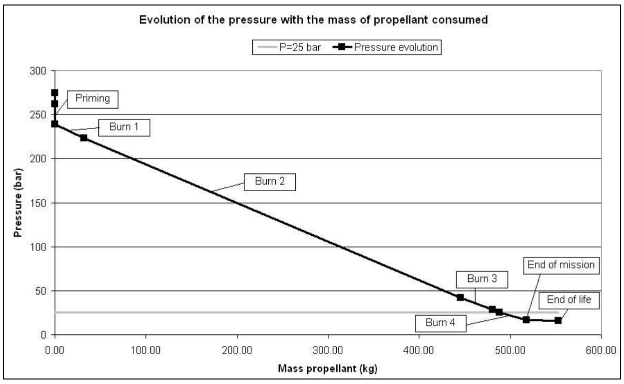

Fig. 2. Evolution of the pressure in the pressurant tank with the propellant consumption.

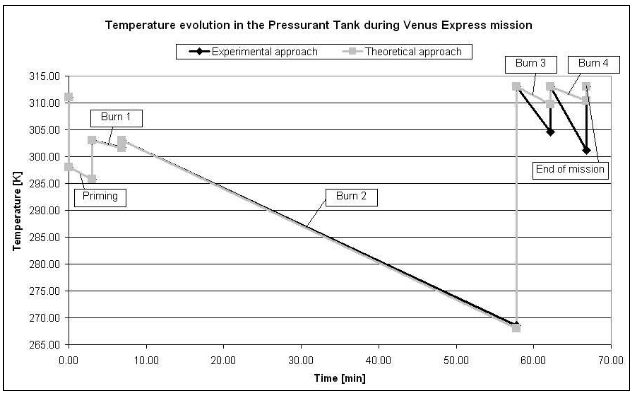

Fig. 3. Evolution of the temperature in the pressurant tank with time.

In order to know the influence of different parameters on the final results, the following tests were carried out:

- The influence of the propellant load and the temperature in the ullage volume on the final pressure of the system at the end of the mission.
- The influence of the propellant load on the final pressure of the system once the propellant tanks of the spacecraft are empty.

4.2. The influence of the parameters on the final results.

4.2.2. Final pressure in the pressurant tank vs. propellant load. Temperature in the ullage volume vs. propellant load.

Fig. 4 shows the evolution of the pressure at the end of the mission and the required temperature in the ullage. On the left-hand side, it displays the final pressure at the end of the mission at different ullage temperatures and on the right-hand side; it displays the required temperature in the ullage in order to have a pressure at the end of mission of 25 bars (minimum operational pressure of the pressure regulator recommended by the manufacturer).

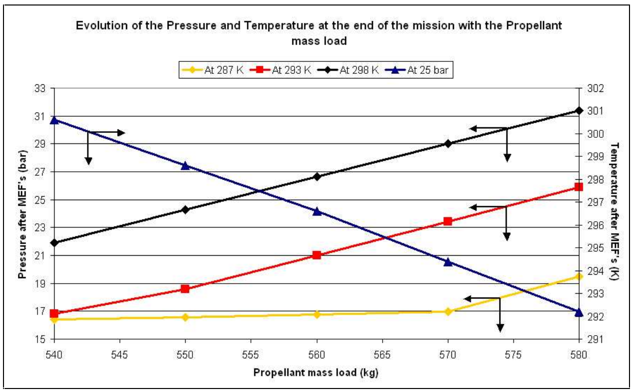

Fig. 4. Final Pressure at the end of mission and the temperature in the ullage vs propellant load.

From the results obtained it can be seen that at higher propellant loads, higher final pressures are obtained. This trend is related with the fact that at higher propellant loads, the ullage volume is lower and thus the amount of Helium required is lower. Therefore at the end of the mission the final pressure is higher.
In addition, it can be seen that at higher temperatures in the ullage volume, the requirements of Helium mass are lower. If the temperature in the ullage is set at 292-293 K or lower the pressure regulator at the end of the mission would be fully opened (the pressure in the pressurant tank and in the propellant tank is the same) and therefore the system will start to work in blowdown mode. On the other hand, at higher temperatures the pressure regulator is not fully opened (therefore the pressure in the pressurant tank is higher than in the ullage tank) and the system will work in regulated mode. The change of the trend of the pressure at 287 K is related with the position of the pressure regulator at the end of the mission.

4.2.3. The final pressure once the propellant tanks are empty vs. propellant load.

Fig. 5 shows the results obtained of the final pressure once the propellant tanks are empty. The analysis of the required temperature in the ullage volume in order to have a pressure of 25 bars was not performed because the temperatures were too high (out of the range of the working conditions of the satellite).

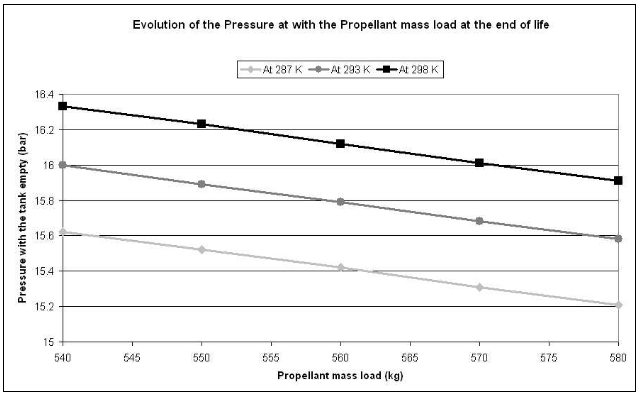

Fig. 5. Final Pressure when the tanks are empty vs propellant load.

When the propellant tanks are empty, the trend of the final pressure with the propellant load is opposite than with the same trend of pressure at the end of mission. This is related with the fact that at higher amount of propellant load, higher amounts of pressurant can be absorbed; therefore the amount of Helium in the ullage volume is lower. At the same volume (volume of the propellant tank), the final pressure will be lower.

4.2.4. Minimum temperature in the pressurant tank vs. propellant load.

Fig. 6 shows the results obtained of the minimum expected temperature inside the pressurant tank at different propellant loads. The calculations were performed at the minimum expected initial temperature in the pressurant tank of 303 K. The minimum temperature corresponds to the second mission phase (the capture) because it is the longest.

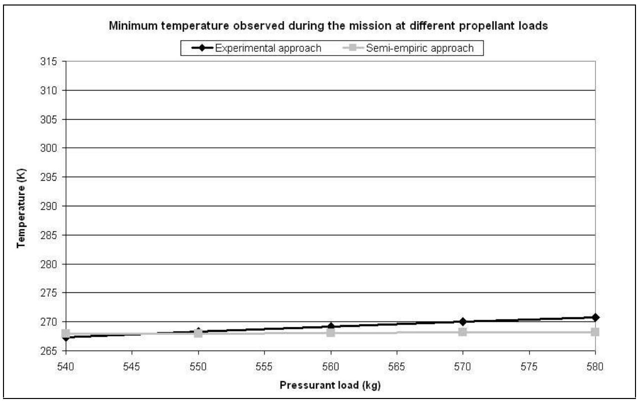

Fig. 6. Minimum expected temperature in the Pressurant tank vs. propellant load.

Fig. 6 doesn't show big differences in the minimum temperature. Maximum differences of 3°C are found for the experimental approach and 0.3°C for the semi-empiric approach. At the same time, both approaches show a certain increase of the minimum temperature with the increase of the propellant load where for the experimental approach the increase seems to be higher.

4.2.5. The propellant consumed when the pressure is 25 bars vs. propellant load.

Fig. 7 shows the results obtained of the amount of propellant that can be consumed with a good functioning of the pressure regulator (in this case 25 bars in the pressurant tank). It is compared at different propellant loads.

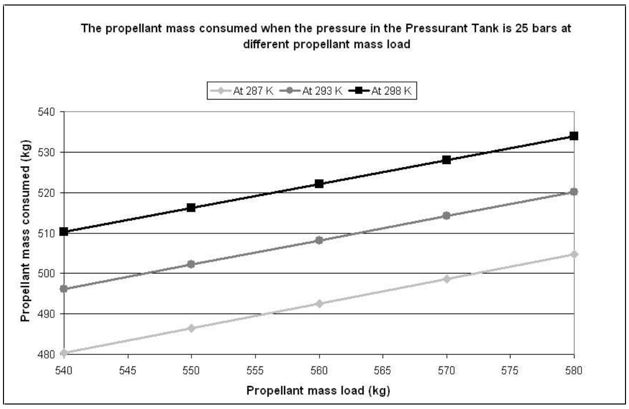

Fig. 7. Propellant mass consumed when the pressure is 25 bars vs. propellant load.

As it was explained in ch. 4.2.2, at higher propellant loads, lower amounts of Helium are required; therefore at the same final pressure higher amounts of propellant can be consumed. The amount of propellant consumed at the end of the mission is estimated to be around 518 kg.

5. CONCLUSIONS

The tool designed shows similar results than the ones shown by the industry in the issue 2 of [1]. Therefore, it is validated for Venus Express mission (a bipropellant systems composed of MON and MMH). For monopropellant systems and the other bipropellant systems, the tool must be still validated.

Venus Express mission

All the parameters of the mission are set except the temperature where a range is given. The worst-case situation corresponds to the minimum expected temperature in the ullage volume and in the pressurant tank (T_{ullage} = 287 K, $T_{Pressurant\ Tank}$=303 K)
Venus Express will have a pressure in the Pressurant Tank at the end of the mission of 16.63 bar if the worst case situation is applied (below the minimum operational pressure of the pressure regulator of 25 bar recommended by the manufacturer). However the manufacturer states that the pressure regulator can work at this pressure. On the other hand, the main thruster was tested to work at lower pressure satisfactorily (although its performance can be reduced). When the propellant tanks are empty the pressure can decrease even more (down to 15.5 bar). To conclude, the working conditions in the last phase of the mission are not usual but in principle, according to the manufacturers, they should have to be sufficient. However, some solutions have been proposed in order to increase the final pressure in the pressurant tanks at the end of the mission:

- **Increase the propellant load**. It increases the total weight of the satellite and can lead to structural problems. At the same time, the pressure when the propellant tanks are empty decreases due to a higher absorption of Helium in the propellant.
- **Increase the temperature of the ullage**. It increases the demand of power and heaters therefore more capacity would be needed.
- **Increase of the initial mass of Pressurant in the Pressurant Tank**. The Pressurant tank should have to be requalified and the safety coefficients are already optimised.
- **Reduce the Pressure Regulator's Pressure.** The demand of Helium is reduced but also the performance of the thruster.

6. REFERENCES

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