A Satellite Platform Modelling with EcosimPro: Simulation and Ground Tests Comparison

Christophe R. Koppel ,KopooS Consulting Ind. Paris (France); José Moral, Iberespacio Madrid (Spain); Marco De Rosa, ESA-ESTEC Noordwijk (The Netherlands), Ramón Pérez Vara, Iberespacio; Johan Steelant, ESA-ESTEC; Pierre Omaly,CNES Toulouse (France)

Abstract. This paper documents the work performed for the implementation and validation of a satellite platform propulsion system modelling library within the existing tool EcosimPro ® and using test cases relevant for space applications.
EcosimPro® is a Physical Simulation Modelling tool that is an object-oriented visual simulation tool capable of solving various kinds of dynamic systems represented by writing equations and discrete events. It can be used to study both steady states and transients. The object oriented tool, with the propulsion library for example, allows the user to draw (and to design at the same time) the propulsion system with components of that specific library with tanks, lines, orifices, thrusters, tees. The user enhances the design with components from the thermal library (heaters, thermal conductance, radiators), from the control library (analogue/digital devices), from the electrical library, etc.

1. INTRODUCTION

The paper presents first a simulation concept that is a system engineering tool dedicated for complex systems, the **E**uropean **S**pace **P**ropulsion **S**ystem **S**imulation (ESPSS) libraries, and in a second part the simulation application for designing and modelling space propulsion sub-systems, in particular for the validation of the simulation results with respect to available ground experimental data.
EcosimPro® is a Physical Simulation Modelling tool developed for ESA by Empresarios Agrupados International (Spain) since 1989. EcosimPro® was a precursor and now with its 20 years of careful growing it belongs to the last generation of the common engineering tools after CAD and integrated engineering analysis tools available on classical PC.
This generation is based on a visual simulation tool for solving simple and complex physical processes that can be expressed in terms of differential-algebraic equations or ordinary differential equations and discrete events. The modelling of physical components is based on a basic “EcosimPro language” (EL), an object-oriented programming language which is very similar to other conventional programming languages (Basic) but is powerful enough to write equations for modelling continuous and discrete processes. EcosimPro employs a set of libraries containing various types of components (mechanical, electrical, pneumatic, hydraulic, etc…) which can be interconnected to model complex multi-domain dynamic systems. The ESA European Space Propulsion System Simulation (ESPSS) is a set of libraries EcosimPro® written to model all aspects of a functional propulsion system.
The Libraries section describes those libraries, focusing on their physical modelling. Some realistic cases of interest are chosen to give an overview of the capabilities of the software. The Validation examples section describes the modelling of these physical systems, and comparisons with experimental data are discussed.

2. ESPSS LIBRARIES

The following libraries have been developed as part of ESPSS: “Fluid Properties”, “1-D Fluid Flow”, “Tanks”, “Combustion Chambers” and “Turbomachinery” libraries. An overview of these propulsion libraries is presented here [2, 9].

2.1 Fluid properties

The fluid properties library is in charge of the calculation of fluid properties. Functions available on this library are mainly used by the 1-D fluid flow library for the simulation of fluid systems.

Three main classes of fluids are available:

- Ideal gases, with temperature dependent thermodynamic and transport properties;
- Simplified liquids, with temperature dependent properties;
- Real fluids, with tabulated properties depending on both temperature and pressure.

where the last class covers liquid, superheated, supercritical and two-phase fluids. Table 1 lists the thermodynamic and transport properties provided in the 2-D tables or calculated for any fluid class.

Table 1: Provided fluid properties

Symbol	Description (Unit)	Symbol	Description (Unit)
P	Pressure (Pa)		
T	Temperature (K)	cv	Spec. heat const. v (J.(kg.K)$^{-1}$)
r	Density (kg.m^{-3})	g	Isentropic exponent (-)
n	Spec. volume (m$^{3}\cdot$kg^{-1})	b	Volumetric expansivity (K^{-1})
h	Enthalpy (J$\cdot$kg^{-1})	k	Isothermal compressibility (Pa^{-1})
s	Entropy (J.(kg.K)$^{-1}$)	v_s	Sound speed (m.s^{-1})
u	Energy (J$\cdot$kg^{-1})	l	Conductivity (W.(m.K)$^{-1}$)
cp	Spec. heat const. P (J.(kg.K)$^{-1}$)	μ	Viscosity (Pa.s)

Two-phase, two-fluid mixtures of a real fluid in any thermodynamic state with a non-condensable (ideal) gas are allowed. The homogeneous equilibrium model is used to calculate the properties quality (mass ratio of vapour/(vapour+fluid)), void fraction (volume ratio of vapour/(vapour+fluid)), etc…) of a real fluid in two phase conditions, with or without a non-condensable gas mixture. User-defined fluids are available for all fluid classes, which can be defined in external data files.

The fluid properties library does not contain any component. Instead, it provides a large collection of functions returning the value of a fluid property (or the complete thermodynamic state) by introducing relevant parameters. In particular, the complete set of fluid state variables (temperature, pressure, density, internal energy, enthalpy, entropy, etc..) is defined by any combination of two independent state variables (for example density and internal energy) for of a pure fluid, and 3 thermodynamic state variables in the case of a mixture of two fluids (for example the two partial densities and internal energy).

2.2 1-D Fluid Flow

The one dimensional "1-D fluid flow" library allows transient simulation of two-fluids, two-phases flow systems. It is linked to the fluid properties library described above, which provides the necessary functions for assessing fluid conditions. Flow inversion, inertia and high speed phenomena are considered in pipes, volumes and junctions. Pipes are also incorporating an area-varying non-uniform mesh 1-D spatial discretisation into n volumes. Concentrated (valves) and distributed (pipes) pressure losses are modelled, and heat transfer between metallic walls and the fluid can be taken into account. Multiple thermo-hydraulic correlations and initialization options are included. Other special components such as check valves, pressure regulators, heat-exchangers and T-junctions are available. 1-D pipe flows can be simulated using some of the most up-to-date, robust and accurate Computational Fluid Dynamics (CFD) techniques: centred schemes and optionally upwind schemes (Roe).

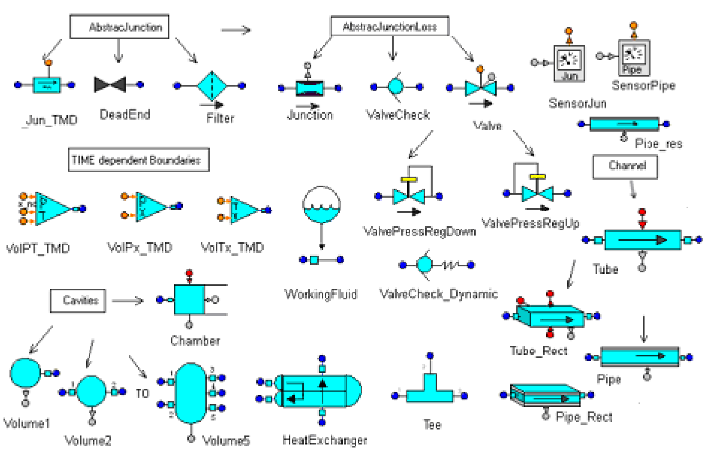

Figure 1: 1-D fluid flow symbol palette

Hydraulic or pneumatic complex systems where heat transfer and control are coupled are easily evaluated with the 1-D fluid flow library. Bubble formation due to the cavitations phenomena or to the presence of a non-condensable gas in a liquid is calculated in pipes or other components. Besides, the 1-D fluid flow library permits to analyze in great detail transient aspects due to inertia (water hammer) and bubble collapse.

2.2.1 Component overview.

Figure 1 shows the main library components. In an EcosimPro fluid network, every component is either a "capacitive component" or a "resistive component".

- A capacitive component receives the flow variables (volumetric, mass and enthalpy flows) as input and gives back the state variables (pressure, density, velocity, chemical composition and enthalpy) at output;
- A momentum resistive component receives the state variables as input in inlet and outlet and gives back the flow variables as output.

To build a fluid network, the user has to connect resistive components to capacitive ones, alternatively. So, from a computational point of view, components are divided into two classes:

- C (capacitive) elements, integrating the mass conservation equation and the energy conservation equation. Thermodynamic functions are used to calculate the complete thermodynamic state;
- M (momentum) elements, calculating explicitly (inertia terms) the mass flows between C elements. It is to be highlighted that reverse flows are allowed.

This computational scheme prevents the appearance of algebraic loops and high index DAE (Differential Algebraic Equations) in the mathematical model of the pipe network.

Pipe component. As an example, a detailed description of the pipe modelling is given. This component simulates an area-varying non-uniform mesh 1-D pipe that exchanges heat with a 1-D thermal port. The general case of a mixture of two fluid components, for which the first one can be either one phase or two-phase, and the second one is non-condensable gas, is simulated through the solution of the following 4 conservation equations:

$$\frac{\partial w}{\partial t} + \frac{\partial f(w)}{\partial x} = \Omega(w) \quad \text{where}$$

$$w = A\begin{pmatrix} \rho \\ \rho x^{nc} \\ \rho v \\ \rho u \end{pmatrix}, \quad f(w) = A\begin{pmatrix} \rho v \\ \rho x^{nc} v \\ \rho v^2 + p \\ \rho v h \end{pmatrix} \quad \Omega(w) = \begin{pmatrix} 0 \\ 0 \\ -0.5\rho v|v| A \dfrac{\Delta\zeta}{\Delta x} - A\rho g + p\dfrac{\Delta A}{\Delta x} \\ \dfrac{\Delta Q}{\Delta x} \end{pmatrix}$$

This set of equations (where v is the velocity, x^{nc} is the non-condensable mass fraction in the total mass) is closed by a thermodynamic equation of state (EoS), which is described in the fluid properties library, and hereafter written under general following forms:

$p = p(\rho, u)$, and in the case of two fluids, three state variables are required to calculate the rest of thermodynamic variables: $p = p(\rho, x^{nc}, u)$.

The choice of density ρ, x^{nc} and internal energy u as independent thermodynamic variables is the most efficient one regarding CPU-time when the EoS is left under arbitrary form.

The different source terms in $\Omega(w)$ are the following:

- In the third equation governing the mixture momentum conservation, a source term represents the equivalent distributed friction: $\Delta\xi$, proportional to Δx, is the pressure drop coefficient.
- In the same equation, another term accounts for gravity, and the last one is responsible for the area variation ΔA and size of the control volume V;

- In the last equation governing the mixture energy conservation is included a source term ΔQ (proportional to Δx) taking into account the heat exchange with the wall surface (S) through a heat port.

The implementation of this set of equations must take into account various parameters, i.e. geometry (flow area and *dx* can vary along the pipe), numerical scheme, boundary conditions, and flow thermodynamics (state law, composition, etc).

Numerical schemes. The tube component is discretized by a centred (optionally either an upwind) numerical scheme. Figure 2 describes the pipe discretisation.

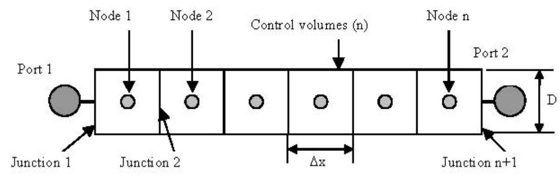

Figure 2: Pipe discretisation

The inner fluxes are computed using one or the other of these schemes, and the first and last junctions (1 and n + 1) ones are given by the fluid ports, as they are calculated at resistive type components using momentum equation with sonic flow limitation. Note that the first and last half-nodal inertia are included in the junction component equations. Using the centred scheme, a staggered mesh approach is applied, for which the state variables (pressure, density, velocity, chemical composition and enthalpy) are associated with the n nodes, and the flow variables (volumetric, mass and enthalpy flows) are calculated at the internal junctions (each junction has associated two half volume inertias). With this scheme, the various fluxes to be computed at the inner junctions are simply the flow variables, except for the mixture momentum flux that is associated to the n nodes. The momentum flux term includes an artificial dissipation term driven by a global parameter so-called “Damp” that allows a reduction of the numerical oscillations.

2.2.2 Tanks

The tanks library enables the transient simulation of rocket engine and spacecraft tanks. As in the 1-D fluid flow library, gas, liquid and two-phase flow regimes can be modelled inside a Tank for ideal or real fluids. Different tank components representing the same physical component (and having formulations with different degrees of sophistication) are available in the Library: homogeneous equilibrium tank (represented by a unique temperature), two zones tanks (gas and liquid tanks), and 1D tanks with n_{liq} nodes in the liquid zone, and n_g nodes in the gas zone. Most typical wall shapes have been included as separated components to model heat conductivity in walls and insulations. Figure 3 shows the main library components.

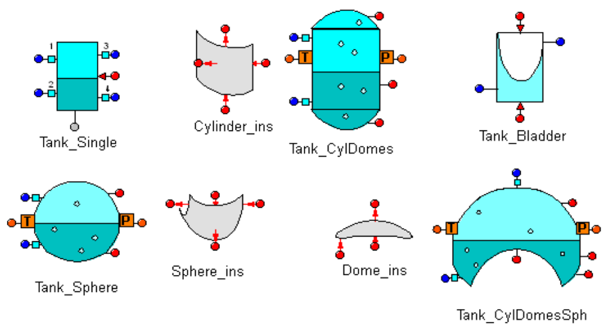

Figure 3: Tanks symbol palette

2.2.3 Combustion chambers

The combustion chambers library enables the simulation of rocket engines and thrust chamber elements. Combustion gas mixture properties (transport and heat capacity) are calculated from adequate coefficients from each chemical species present as combustion product. Minimisation of Gibbs free energy is applied to find equilibrium molar fractions for a mixture of reactants. Figure 4 shows an overview of all combustion chambers components.

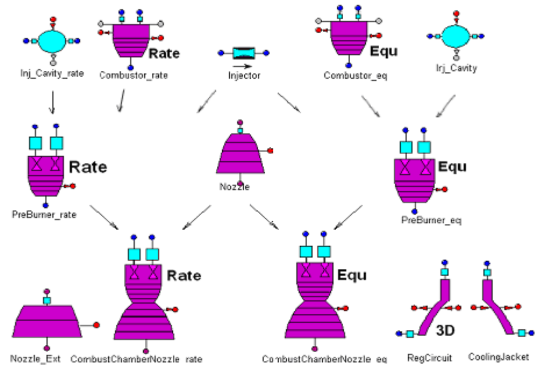

Figure 4: Combustion chambers symbol palette

The 1D combustor components has the main advantage of being able to simulate start-up and shutdown sequences. They can be directly connected the respective pipes, valves and regenerative circuits of a real engine system. In this respect, many cases have been run successfully for modelling different kind of cycle engine (gas generator cycle, staggered cycle and expanders' cycle) where the turbomachinery and the feeding tanks are included.

2.2.4 Turbomachinery

Turbomachinery is an EcosimPro® library for the simulation of pumps, turbines and compressors. Pump components are provided with dimensionless turbopump characteristics curves adapted to positive and negative speeds and flow zones. Turbine and compressor components are provided with dimensionless performance maps as a function of the reduced axial speed and pressure ratio. Figure 5 shows the main library components.

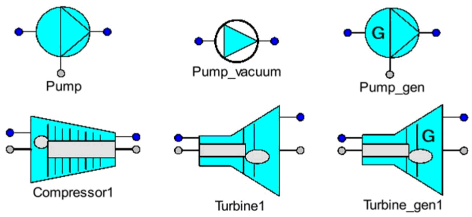

Figure 5: Turbomachinery symbol palette

2.2.5 Other compatible libraries

Three libraries part of the EcosimPro software are compatible with the ESPSS libraries described here: the thermal library, the mechanical library and the control library. Their components can be easily used along with the ESPSS components. A short description follows for each of these libraries:

Thermal library. This library provides components for the prediction of temperature distributions and heat flows in systems and devices using the thermal network method. The thermal network method is also known as the lumped parameter method or the resistance/capacity method. It is essentially a finite difference method and involves modelling a continuous medium as a discrete thermal network of nodes representing the capacitance of the system linked by conductors representing its conductance. The modes of heat transfer that can be considered in thermal model are conduction, radiation and natural convection. Additional features allow the handling of phase-change phenomena using components called "DNphases".

Mechanical library. The mechanical library allows the modelling of 1-D mechanical systems. Most of the typical mechanical units are included as components that can be used to build graphically complex systems:

- Translational components for systems with linear displacements driven by forces with frictional losses
- Rotational components for systems with angular displacements driven by momentum with frictional losses
- Kinetic converters (levers, gears, ideal gear rotational to translational) transform an angular movement into other angular movement at different velocity or into a translational movement.

The most important elements can be grouped in the following groups: masses and inertia (Sliding mass, End stop mass, Inertia and End stop Inertia), which implement the second Newton law. Force and torque generators (Coulomb friction, dampers and springs) calculate force or torque from the position or the velocity in their ports. Actuators (force, position, torque, acceleration and angle generators) provide force, torque, acceleration, position and angle depending on an external input signal (user defined law).

Control library. This library provides the custom items needed to represent analogue and digital control systems. All basic operations can be performed on analogue or digital signals (addition, multiplication, multiplex/demultiplex, derivative, integral, logical operations), and some more advanced control operations are implemented (linear or discrete space-state, filter, PID control, transfer functions, etc.).

3. VALIDATION: FILLING OF STRAIGHT EMPTY TUBES

The filling of a straight empty tube from a pressurized tank ($P_{\tan k}$), induces at the end of the filling a first water hammer peak pressure (ΔP) followed by, after a rather long duration ($\Delta TIME$), a second water hammer peak having lower amplitude (ΔP_2). This typical behaviour can be assessed roughly for the first peak pressure (Joukowsky, cited in [1]) and for the duration (Wylie and Streeter, cited in [1]) by the two following simple equations:

$$\Delta P = a.\rho.v \quad \textit{and} \quad \Delta TIME = \frac{\Delta P}{P_{\tan k}} \cdot \frac{2.L}{a}$$

where a is the speed of sound (see sketch on fig. 7). There are no simple equations for the assessment of the amplitude of ΔP_2, except that the damping, due to the friction on the tubing walls, allows a reduction of the velocity v, hence we can only know that $\Delta P_2 < \Delta P$.

In order to validate the computations performed by the tool EcosimPro® with the equations set into the libraries ESPSS, the tests data from existing ground experiments provided by CNES [6] have been compared to the results of the modelling.

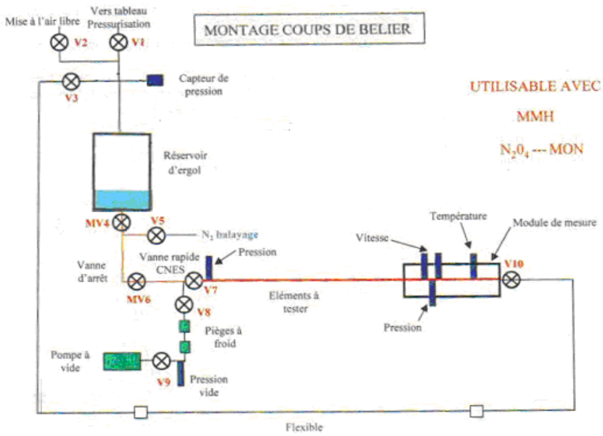

Figure 6: Test set-up for Water hammer tests

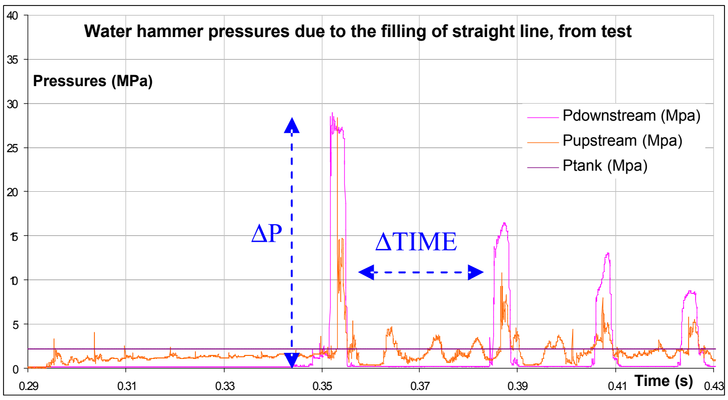

Figure 7: Water hammer pressures from tests

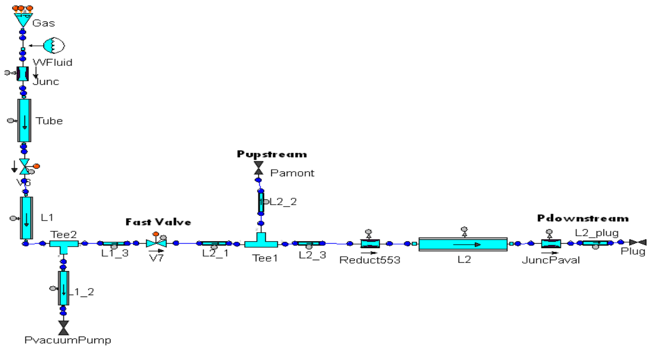

Figure 8: Test set-up for water hammer under EcosimPro® with objects of ESPSS

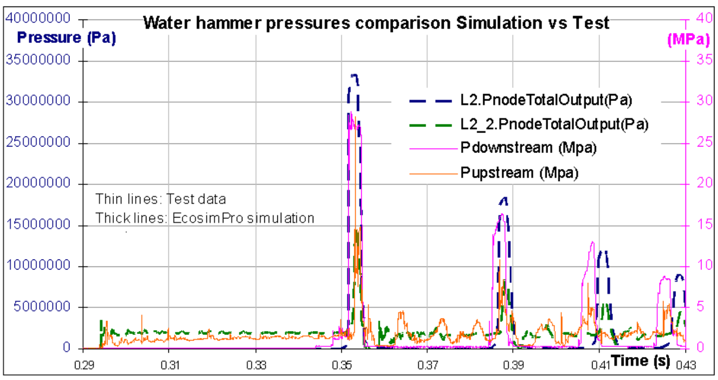

Figure 9: Water hammer pressures comparisons

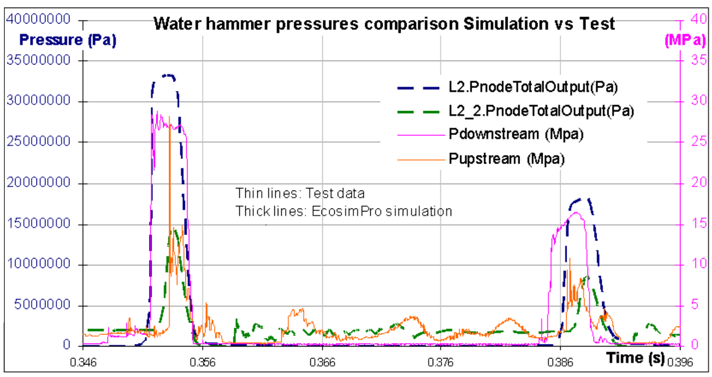

Figure 10: Large zoom of the two firsts water hammer pressures: simulation results are robust and safe

The test setup, described in references [4,5,6], is defined by a line filled up to the fast valve V7 that isolate the empty line up to the valve V10. Two main pressures measurements are available $P_{upstream}$ near V7 and $P_{downstream}$ near V10.

The pressure outputs of the ground test are shown in fig. 7. Based on the test set-up, using exclusively the generic objects of the library ESPSS [3], with the particular dimensions of the hardware, the model on EcosimPro®, fig. 8, looks identical to the hardware set-up fig. 6.

As shown on fig. 9 and fig. 10 the results of the simulation are surprisingly good with respect to the experimental ground data: very similar peak pressures for the first peak pressure (a little bit higher for the simulation: that is a quality of robustness of the simulation for being used safely operationally for designing and for the justification of the design), the duration between the two firsts spikes is also nearly identical and the damping for the second pressure peak is also very compliant with the experimental data.

4. VALIDATION: FILLING A SATELLITE MANIFOLD

A similar validation of the water hammer occurring in satellite tubings has been undertaken with tests data provided by CNES from a real satellite functional model of the CNES satellite “Stentor” [7].

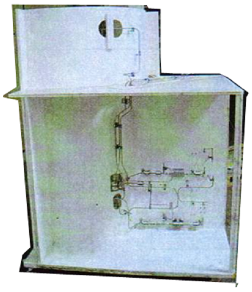

Figure 11: Satellite hardware

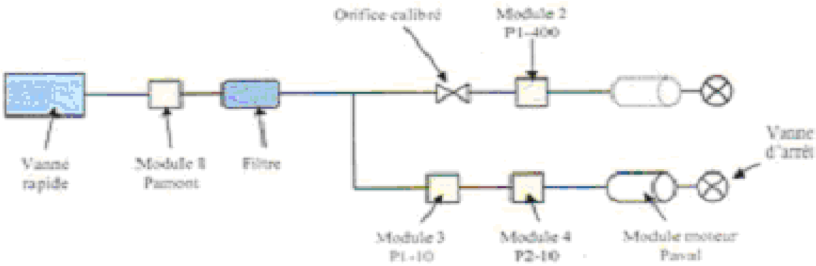

Figure 12: Sketch of the Tee tubing to be filled

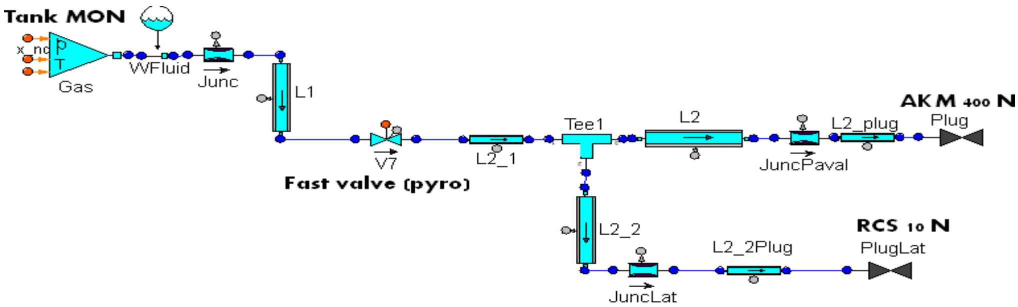

Figure 13: EcosimPro® model with objects of ESPSS (the calibrated orifice is included into the Tee1 data)

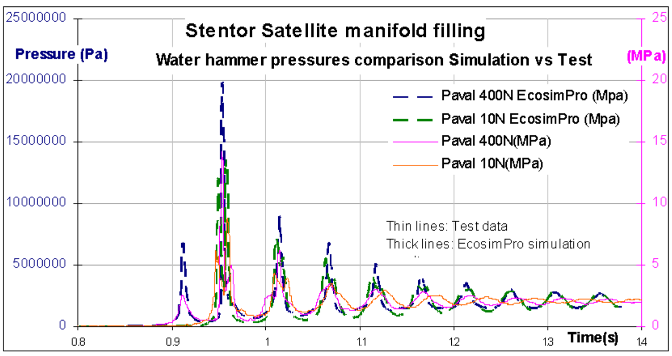

Figure 14: Water hammer pressures comparisons

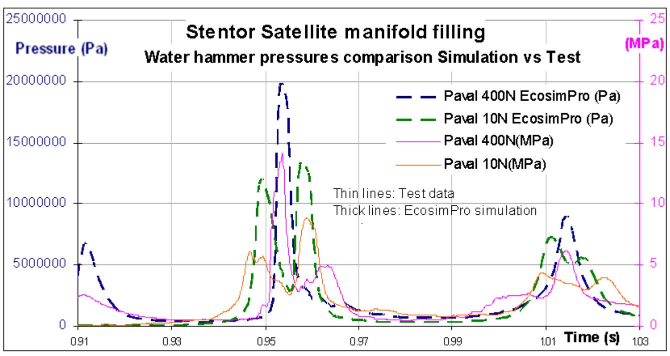

Figure 15: Large zoom of the sequence of firsts pressures spikes: simulation results are safely robust

As shown on fig. 14 and fig. 15 the results of the simulation are surprisingly similar to the experimental data, with a safe robustness for the simulated pressures that are always higher than the pressures obtained in experimental tests, and in addition the complex sequences of the successive pressure spikes (due to the non-simultaneous filling of each of the two downstream branches of the tee tubing) computed by EcosimPro® is strictly conform to the one of the experimental data.

5. VALIDATION: BUTANE PRESSURISATION

The validation with ESPSS of the behaviour of biphasic mixtures under dynamic process of pressurisation and expulsion has been made possible thanks to available data for Butane propulsion [8]. The set-up of the feed system is composed of a very well thermal-insulated storage tank with heaters, fig. 16. The output line includes valve, tubing and mass flow regulator, as sketched in fig. 17.

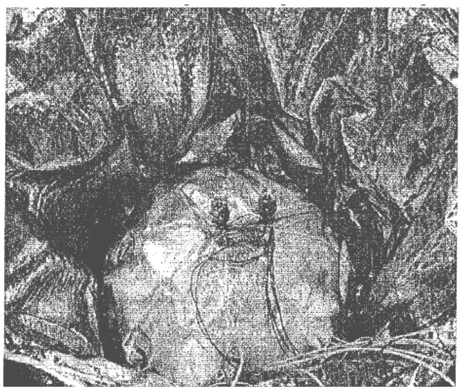

Figure 16: Tank insulated

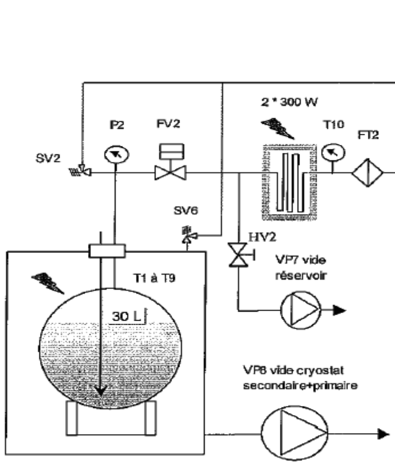

Figure 17: Sketch of the experimental set-up

A typical sequence of the ground tests was, from ambient condition, a first phase long duration heating of the tank in order to reach a significant pressure inside the tank, and then a second phase of expulsion of the gaseous phase at constant mass flow rate in order to simulate the feeding of the thrusters.

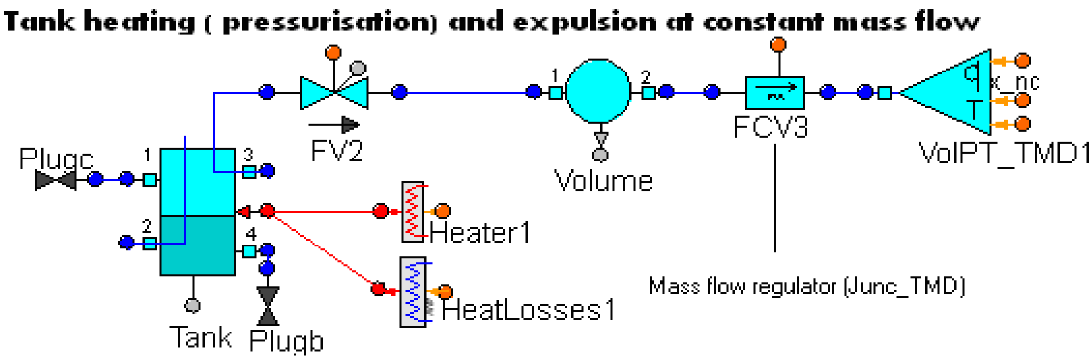

Figure 18: Test set-up for Butane test under EcosimPro® with objects of ESPSS

As described above, using the generic components of the ESPSS libraries, the model on EcosimPro®, fig. 18, looks identical to the functional part of the hardware set-up of fig. 17. The simulation on EcosimPro® starts by the heating of the tank for a duration of 39600 s [8]. Then the expulsion phase occurs for duration of 7200 s. The results of the ground test during the expulsion phase are shown in fig 19 and the output of the simulation tool (with pressurization followed by expulsion) is shown in fig 20. The quantitative results for the heating phase with the real experimental test and the simulation is shown in table 2. The results are very similar. This shows the suitability of the data and equation used into ESPSS for solving the problem of heating a biphasic mixture.

Table 2: Comparison of Experimental and simulation

Heating phase	Temperature initial to final (K)	Pressure initial to final (MPa)
Ground test	283 to 329	0.140 to 0.580
EcosimPro simulation	283.5 to 327	0.151 to 0.553

The quantitative results for the expulsion phase with the real experimental test and the simulation is shown in table 3. The results are almost identical. This shows once more the suitability of the data and equations used into ESPSS for solving the problem of managing a biphasic mixture.

Table 3: Comparison of Experimental and simulation

Expulsion phase	Temperature initial to final (K)	Pressure initial to final (MPa)
Ground test	327 to 284	0.5515 to 0.153
EcosimPro simulation	327 to 283.5	0.5519 to 0.151

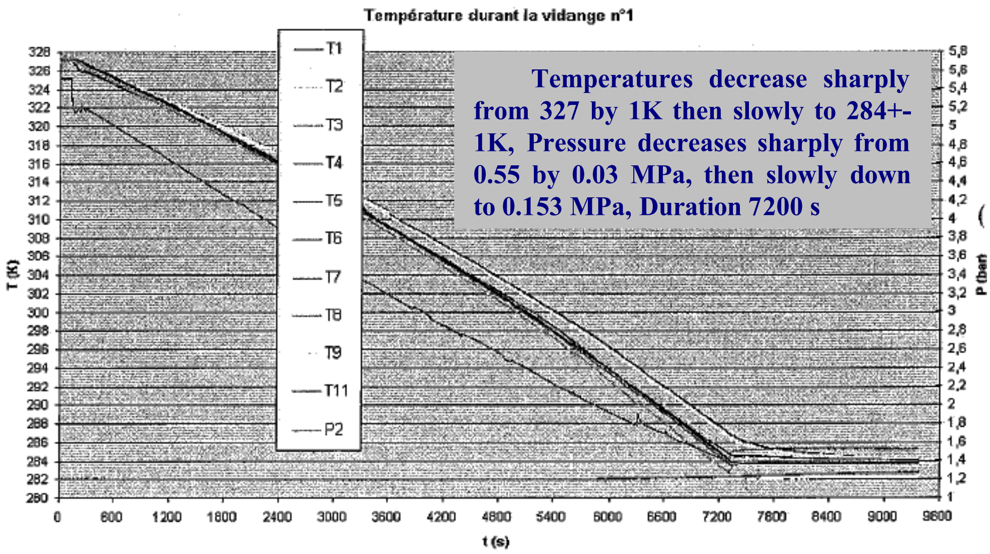

Figure 19: Results of ground tests during the expulsion phase: several tank skin temperatures and tank pressure

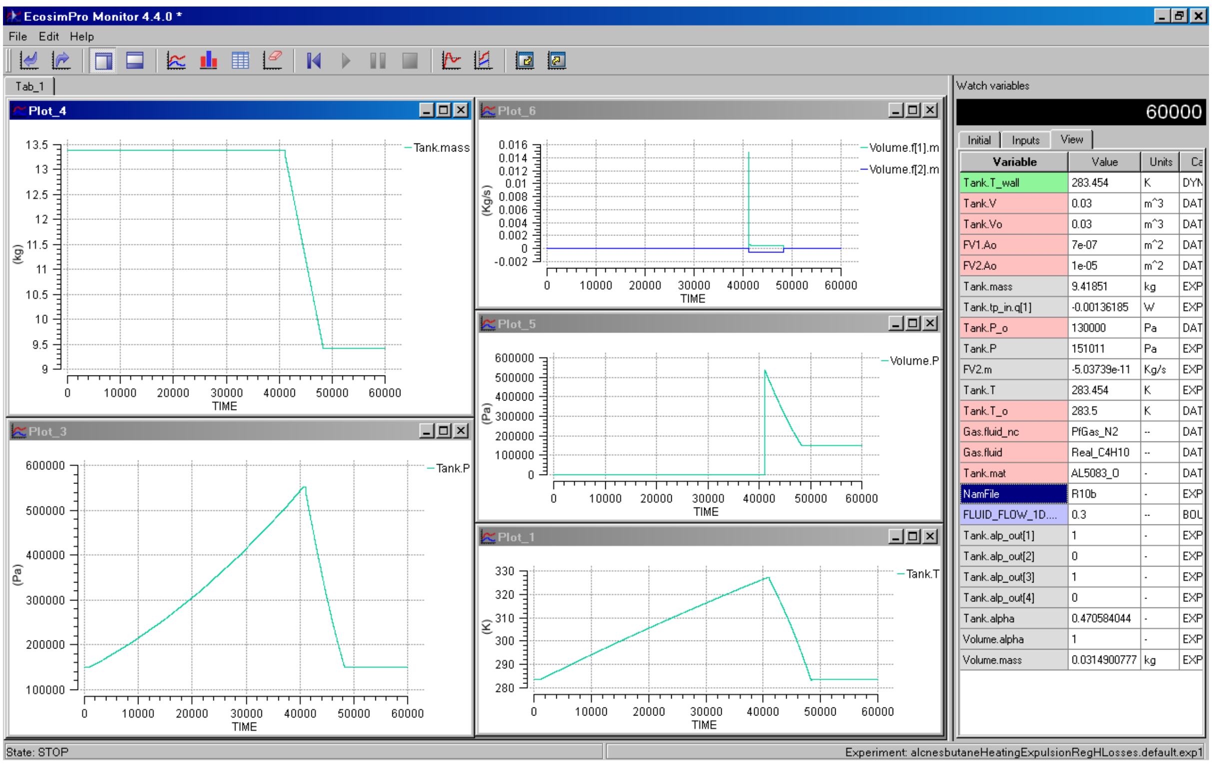

Figure 20: Output of the simulation tool up to 60 000 seconds: mass, pressure, mass flows and temperatures (with butane real gas)

CONCLUSION

The Physical Simulation Modelling tool EcosimPro® with the ESPSS libraries has been presented and assessed for several validation cases relevant in the area of the propulsion sub-systems for satellite platforms. The results of the simulations show good compliances with the experimental results on ground.

In addition for the water hammer pressure the simulation produces slightly higher pressures than the experimental data. This robustness enables the use of the tool and library for operational purpose, for designing safely the propulsion systems and with a drastic reduction of the tests to be performed for the justification of the design.

The main advantage of using this new generation of simulation tool is the ability to manage complex systems, sub-systems and their components like objects for several different engineering purposes. There was no need to develop several software tools, one for water hammer purpose and another one for biphasic mixture purpose: the components described by equations into the unique set of libraries into ESPSS can be used like hardware components for solving or assessing many different problems saving lots of efforts and money. In addition, by carefully analyzing the obtained simulation data, this class of tools can highlight the occurrence of certain conditions necessary to trigger particular phenomena, e.g. the so-called "adiabatic decomposition of hydrazine" during the filling of the lines, etc.

EcosimPro® is already used successfully for several space applications and in many other areas, the fidelity and quality of the simulations obtained make that this new generation of simulation concept with libraries like ESPSS will become in the next years a commonplace as CAD stations are today.

ACKNOWLEDGMENT

The authors want to express their special thanks to CNES-Toulouse for providing the very valuable tests data. The overall activities have been performed in the frame of an ESA/ESTEC Contract 21490/08/NL/CP.

REFERENCES

1. Anton Bergant, Angus R. Simpson, A. S. Tijsseling. “Water hammer with column separation: A historical review,” Litostroj Ljubljana; University of Adelaide, Australia; Eindhoven University, *Journal of Fluids and Structures* 22, 135-171.

2. M. De Rosa, J. Steelant, J. Moral, Y. Elkouch, R. Pérez Vara, ESPSS: European Space Propulsion System Simulation, *5th European Space Propulsion Conference*, Heraklion, Crete, 5 – 8 May, 2008.

3. Library ESPSS dated March 2008.

4. I. Gibek, Y. Maisonneuve, “Waterhammer Tests With Real Propellants,” AIAA 2005-4081, *41st Joint Propulsion Conference and Exhibit*, 10-13 July, 2005, Tucson AZ.

5. R. Lecourt, J. Steelant `Experimental Investi-gation of Waterhammer in Simplified Feedlines of Satellite Propulsion System', AIAA Journal of Propulsion and Power, Vol. 23, No. 6, pp 1214-1224, Nov.-Dec., 2007.

6. Y. Maisonneuve, J Maunoury, “Etude expérimentale du phénomène de coup de bélier en ergols réels,” *Confidentiel Onera-Cnes, RT 1/06416 DMAE Version 2* – Août, 2005.

7. Y. Maisonneuve, J Maunoury, “Etude expérimentale du phénomène de coup de bélier sur réseau ,” *Confidentiel Onera-Cnes, RT 4/10570 DMAE* – Novembre, 2007.

8. A. Ravex, S. Bur, P. Bravais, “Rapport d'essais des essais de soutirage C4H10,” *Confidentiel AirLiquide-Cnes, D8014-NT-010 (0)* – 29 novembre, 2007.

9. C. Koppel et al., "A Satellite Platform Modelling with EcosimPro: Results of the Simulation Compared to the Ground Tests", *SimTecT 2009 Simulation Conference and Exhibition,* Adelaide, Australia 15-19 June, 2009.