An Overview of the ESPSS Libraries: Latest Developments and Future

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ABSTRACT

The European Space Propulsion System Simulation (ESPSS) libraries, based on the EcosimPro platform, have become the ESA's standard tool for the design and analysis of space propulsion systems along all project phases. Furthermore, the libraries are also the preferred tool for the main European companies and institutions in the space propulsion field. This fact has been possible thanks to the continuous developments and the improvement process established, where the involvement of the users, providing their feedback, suggestions and demands of lacking capabilities based on their experience of use, is key to obtain a state-of-the-art tool, always adapting to the newest needs. This paper presents the overall status of the ESPSS libraries, describes the most relevant updates included in the latest official version thanks to the different projects carried out recently and gives some ideas about future lines of development and new capabilities identified as potentially interesting for the users.

INTRODUCTION

The creation of the ESPSS libraries was proposed to set up a common European platform for the design, analysis and simulation of space propulsion systems. In a context where each company or institution working on space propulsion developed its own software, ESPSS was the initiative of the European Space Agency to join forces and promote the use of a common tool, pursuing several benefits:

- The use of engineering simulation tool able to model all systems in the propulsion line concatenated from tank up to the nozzle exit
- The use of an open source library for simulating various physical phenomena and propulsion (sub)system(s), allowing users to modify or extend the formulations based upon their won background and expertise
- The provision of a common propellant database with capabilities to interchange among companies easily component representations on the same platform
- A reduction of software development and maintenance costs, entrusted to a dedicated and specialized team
- A faster and wider evolution of the tool thanks to the involvement of a varied group of private companies and public institutions, each of which contributes with its expertise to the final common product
- The interaction with several other engineering tools (e.g. ESATAN) as well as high-fidelity codes such as CFD-tools in terms of zooming at component level [3][7][8][9][10].

After a first de-risk prototyping exploration phase, the first development of the libraries started in 2006 within a consortium formulation, following a collaborative proposal and led by Empresarios Agrupados Internacional (EAI), a Spanish architect-engineering company with wide knowledge and expertise in software development and thermo-hydraulic simulation activities.

The first official version of the libraries was released in 2008 [1] and since then new versions are produced annually, including new features suggested by the users, correction of issues detected or adaptation to technological progresses (e.g., better code compilers, faster solvers, etc.).

The main purpose of the ESPSS toolkit is the definition and analysis of complex two-phase, two-fluid and multi-species (combustion) systems under transient and steady conditions, specially adapted to the simulation of propulsion systems for launchers and satellites. It is structured in several libraries, comprising the following features:

- A wide, built-in database of properties of fluids, allowing the use of several categories of pure fluids and homogeneous mixtures
- Generic approach for all the components, making them independent on the working fluid selected
- Components to represent fluid networks, in which phenomena such as transient effects (water-hammer), single and multi-phase, heat exchange or control processes can be easily analysed

- Pressurization systems including priming processes, tanks, mechanical or electronic pressure regulators
- Combustion phenomena, taking into account non-adiabatic conditions and vaporization, and obtaining the chemical equilibrium of the products
- Liquid rocket and special combustors such as hybrid and solid rockets or air-breathing engines
- A specific library for the calculation of steady performances of liquid rocket engine cycles under design and off-design conditions
- Libraries for the preliminary analysis of orbits and attitude of satellites, and for electric propulsion systems

In addition to Space Propulsion, EcosimPro is ESA's preferred tool for the simulation of Environmental Control and Life Support Systems (ECLS) or Power Systems.

The use of these toolkits is based on EcosimPro, a general-purpose simulation tool also developed by EAI. This fact gives an additional advantage to the whole, since the developments of the libraries are aligned with those needed in the platform. EcosimPro incorporates the following main features:

- A user-friendly Graphical User Interface (GUI)
- Encapsulation (object-oriented programming), enabling the abstraction of component's behaviour into components
- Non-causality, the components don't need to define explicitly the system of equations since the final ordering will be done by EcosimPro automatically
- Inheritance, enabling joining the behaviour of a parent component into the inherited one
- Aggregation, which permits the creation of complex components or models thanks to the connection of multiple instances of single components
- State-of-the-art transient and steady solvers
- Many built-in options to exchange and share models or model data and to connect to other tools (FMI, OPC-UA, Excel and Matlab/Simulink add-in, etc.)

In this context of continuous development, this article aims to present the latest features included in the ESPSS libraries, as well as a roadmap of potential improvements that were suggested as relevant for future releases.

LATEST PROJECTS

The continuity of ESPSS rests on two main categories of projects:

- The Maintenance program, focused on the resolution of issues detected during the usage of the tool reported by any user. This category also includes small developments of capabilities manageable in a short period of time
- Development projects, oriented to the inclusion of complete, new features that require longer implementation phases

Prior to the present fourth phase on Multi-Phase development, three phases were completed:

- First phase aimed to achieve basic core capabilities for a space propulsion systems simulation tool [1]
- Second phase was based on a basic validation of the tool for realistic, industrial systems [2]
- Third phase pursued several developments based on previous phases experience and feed-back: upgrade of models (tanks, pipes, turbo-machinery) and creation of new libraries (STEADY, SATELLITE, EP) [4][5][6][8][10][11]

Following list collects a selection of updates included in ESPSS 3.2.4 during the latest development and maintenance projects, classified by library.

FLUID_PROPERTIES Library:

- Adaptation to LINUX (only decks)
- Added function to retrieve the thermodynamic state from conservative variables (FL_state_vs_rh, thermodynamic state versus density and enthalpy)
- New formulation to calculate slush properties
- The formation enthalpy of perfect liquids H_2O_2, JP-10, MMH, NTO, Jet-A, and N_2H_4 are improved to take into account the latent heat (especially relevant when used for combustion)
- Properties of simplified liquids are improved accounting for a non-null vapour pressure, hard-coded to 100 Pa, which allows bubble formation/collapse under extreme conditions and avoids undetermined equations (for a more precise calculation, the use of real fluid properties is required)
- THERMO_TABLE_INTERP Fortran Library is improved with faster performances thanks to the compilation with INTEL

FLUID_FLOW_1D Library:

- Added a new Pipe component for non-homogeneous two-phase flow (beta version)
- Added flow coefficient (CV) formulation for Junctions and Valves and automatic pressure drop calculation at any branch of a Tee
- New heat exchange correlation for Pipes including roughness effects [15]

- Added new Plate-Fins heat exchanger component: two alternated currents in counter-flow disposition along several plates' levels
- Ghost and numerical fluxes values for ROE/AUSM schemes in Pipes are better calculated from the enthalpy and volumetric (Q) junction flows
- Intake component is improved to better calculate the mass flow, according to the total pressure recovery
- Calculation of the slush mass fractions in volumes and pipes with the melting solid properties as an input through the files of real fluid properties

COMB_CHAMBERS Library:

- New heat exchange correlation for Cooling Jackets including roughness effects [15]
- Improved calculation of the reaction heat needed for the pyrolysis/decomposition of the solid propellant
- Improved calculation of the lateral consumption of solid propellants; new options and geometries for hybrid and solid combustors using the 2D axisymmetric SUMO code

ATD Library:

High speed vehicles require special thermal considerations, not necessary for conventional flights, because of the higher heat loads they receive during flight. Consequently, the designs of the aeroshell and the thermal protection system have to be able to maintain the temperatures within the range of operation, whether evacuating the heat received or accumulating it to be evacuated after landing; a specific library called ATD is available in ESPSS to design and test said thermal systems [16].

SATELLITE Library:

A relevant upgrade was done to the SATELLITE library to prepare it for its coupling to detailed propulsion systems. Modifications were performed in the Frame component in order to receive inputs from the propulsion system, e.g. thrust or tank mass, and calculate overall forces, accelerations and rotations of the vehicle based on the Archimedes equation; components from other libraries were also updated accordingly, making them able to provide/receive the variables to/from the Frame [8][10].

Figure 1 contains the ESPSS model showing the coupling capability and *Figure 2* presents results on orbit and acceleration calculation.

User Manual improvements:

- Inclusion of tutorials to better help the user in building models, especially concerning the input data description and the Valves formulation
- New illustrative priming example describing the effects of Junctions and Tees in a circuit
- New illustrative test cases for a combined-cycle air-breathing rocket engine working in design and off-design conditions
- New section “Excel-ESPSS connection example”

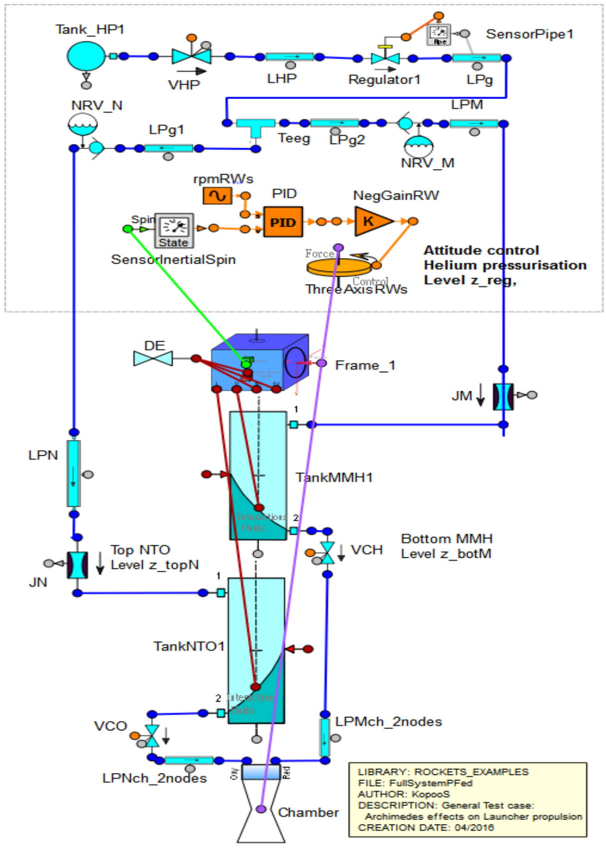

Figure 1 *ESPSS schematic for propulsion/AOCS coupling*

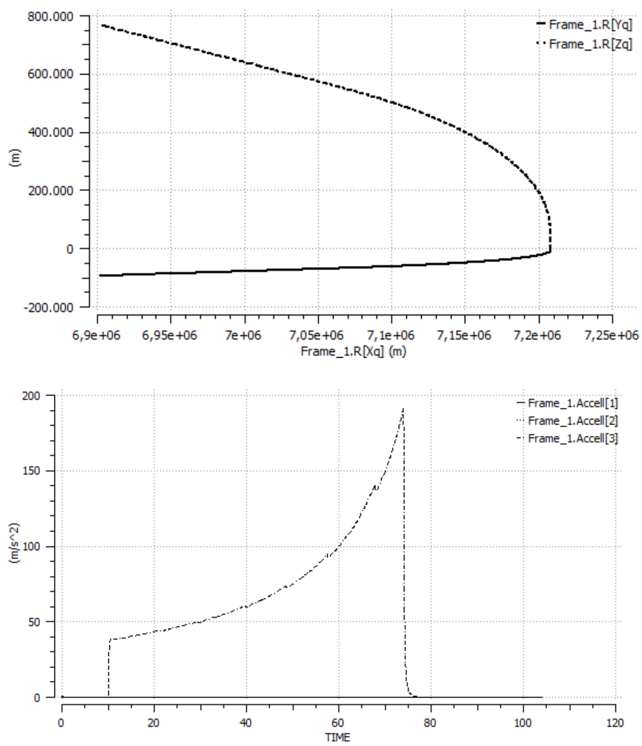

Figure 2 *Results of the coupling model: orbit calculation (upper plot) and accelerations (lower plot)*

The next sections below focus on two remarkable new capabilities included in ESPSS latest release 3.2.4:

- The non-homogeneous two-phase pipe component
- The extension of the fluid properties range to the slush phase

NON-HOMOGENEOUS TWO-PHASE PIPE

One of the noted features of ESPSS is its capability to simulate, assuming homogeneous equilibrium model, two-phase fluid systems, either as a single fluid at saturation conditions, or as mixtures of a liquid with a non-condensable gas. The current model (HEM) assumes that both phases are at homogeneous equilibrium within each control volume, that is, pressure, temperature and velocity are common in the liquid and in the vapour.

The implementation of a non-homogeneous two-phase model in the libraries is, without a doubt, the most relevant development pursued in ESPSS. The Von Karman Institute has led this activity in close collaboration with “La Sapienza” University of Rome and EAI. The efforts done in this direction over the latest years have proven the difficulty to obtain said model with the expected level of robustness.

Some specific issues for multi-phase flow simulations were tackled during the development phase, e.g.:

- The non-homogeneous two-phase flow approach selected requires the use of the time derivative of the quality α’
- Formulations for multi-phase flow models are not necessarily hyperbolic as in single-phase flows, making the implementation not trivial; particular solutions worked out worldwide by the multi-phase simulations community were implemented
- Phase changes represent a singularity in the equations proposed, making the system unstable and prone to non-convergence

A beta version of the non-homogeneous two-phase Pipe component has been released within the latest ESPSS version 3.2.4. The development of this component continues, as more work has to be done to obtain a fully robust model and several items have been identified as desired improvements:

- Include source terms for phase change, two-phase friction and energy exchanges
- Handle mixtures of non-condensable gases and vapours of the main fluid
- Implement different flow regimes (independent bubbles, packed bubbles, slug flow, churn flow, annular flow)
- Enable assemblies of the two-phase Pipe with the conventional ESPSS components
- Validate exhaustively the new model against experimental databases

For more information on this particular development on AUSM numerical scheme and the related multi-phase implementation, the reader is referred to the work of F. Pinna and M. Leonardi [9][14].

The ESPSS schematic created to test the model against literature values and some results obtained are shown in *Figure 3* and *Figure 4*:

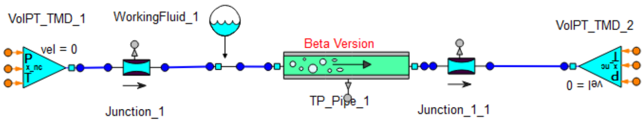

Figure 3 *ESPSS schematic for the shock tube test case*

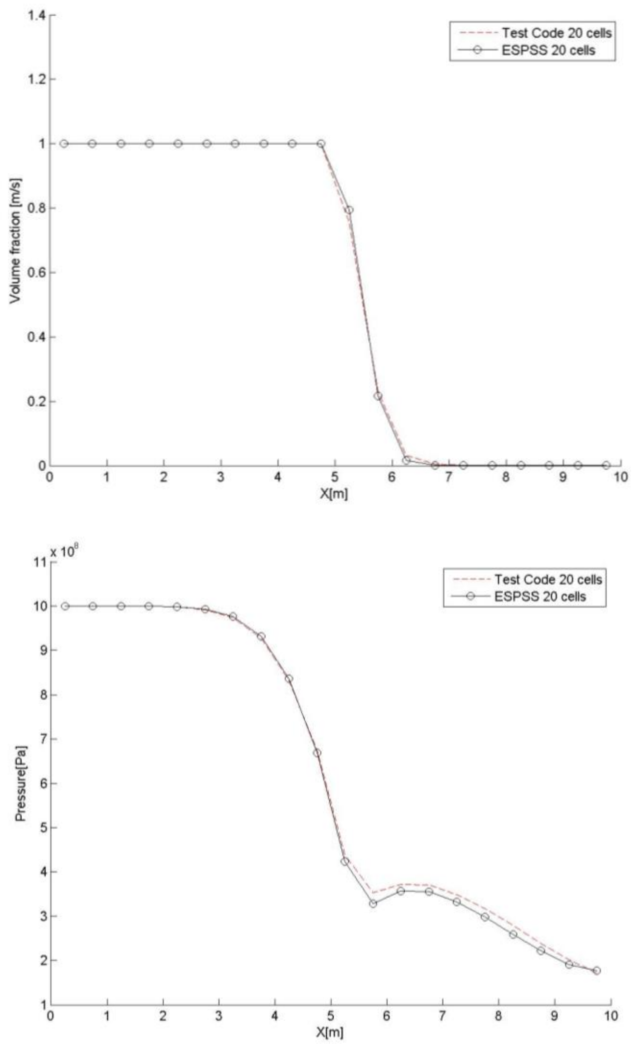

Figure 4 *Shock tube test case results vs. test code: volume fraction (upper plot) and pressure (lower plot)*

EXTENSION OF PROPERTIES: SLUSH

The term slush is used to refer to a mixture of solid, mostly present as small ice crystals, and liquid phases of a fluid when cooled below the melting line down to the triple point. This leads to increased densities with respect to the liquid state and avoidance of boil-off losses. Slush propellant has thus an attractive application to space launchers.

The objective of extending the fluid properties database towards the solid region is to accurately consider the mixture properties in that phase, when ice crystals start to form inside the liquid.

In order to be consistent with the rest of the formulation in ESPSS, the implementation is based on handling a new two-phase region for the solid-liquid interface, similar to the existing liquid-vapour region. To do so, three modifications had to be addressed:

- Upgrade of the reading and interpolation routines
- Extension of the built-in database of properties of fluids to include the solidification line
- Adaptation of the ESPSS functions and components to the new capability

Upgrades of the reading and interpolation routines

Providing the capability to extend the database of fluid properties to the solid phase region implied modifications to the reading and interpolating functions of the tables of properties. In addition to that, the handling of special situations and errors had to be reviewed and adapted to this new functionality.

The ESPSS function that reads in and interpolates from the property tables is "thermo_table_inerp" and is encapsulated in an external library. This function was the object of the most important modifications.

Reading

In addition to the existing actions, a new loop was implemented to read the properties of the solidification line.

The execution of the new loop depends on the existence of solid properties in the file of the fluid in use. Three scenarios are possible:

- If no properties are found the reading is skipped and the simulation preserves the original behaviour
- If solid properties are incomplete or the format is incorrect, an error message is produced and the simulation continues as if no solid properties were available
- If there are properties available and the format is correct the reading continues normally

In the latter case, the solid properties are stored in a new internal variable. Then, a mapping of properties on the solidification and melting lines is done to have the properties at the same grid points (e.g. properties at the same pressure level on both the solid and liquid side). This step is required for the interpolation routine in order to work properly, as the number of property points added is free, but the biphasic region interpolation needs the same value of the independent property at both solid and liquid sides.

Interpolation

A profound revision has been carried out to include the detection of the solidification region in the interpolating functions.

Currently, the libraries consider two types of interpolations depending on the independent variables used:

- Direct ("y_f_px" function), using the couples p-s, p-h, p-T, p-u, p-ρ, and returning the requested property
- Reverse ("p_f_xy" function), using the couples h-s or ρ-u and returning pressure

The formulation of the one-dimensional components is based on the integration of the conservative variables ρ and u, whereas other functionalities require a direct entry into the tables (e.g. pressure and temperature initialisation of components). Therefore, both direct and reverse interpolation types are needed and were updated to consider the solidification region.

The methodology implemented to detect the fluid state is slightly different depending if the interpolation is direct or reverse.

First is explained the direct interpolation. The concerned fluid property is a function f(P,x), where "x" can be h, u, T, ρ or s (note that two-phase conditions are not fully specified if P-T is used):

- $x < x_{melting}$ → two-phase solid-liquid conditions. Quality (q) is determined with the following equations, iterating in pressure:

$$q = \frac{u - u_{liq}}{u_{sol} - u_{liq}} \qquad \textit{Eq. 1}$$

$$\frac{1}{\rho} = \frac{1}{\rho_{liq}} + q \cdot \left(\frac{1}{\rho_{sol}} - \frac{1}{\rho_{liq}}\right) \qquad \textit{Eq. 2}$$

- If P > Pcrit → 2D interpolation in the supercritical region
- Otherwise, the vapour two-phase limit at the current pressure shall be interpolated, being x_g the value of property x at vapour-side saturation:
  - If $x > x_g$ → 2D interpolation in the super-heated vapour region
  - Otherwise, the liquid two-phase limit at the current pressure shall be interpolated, being x_l

the value of property x at liquid-side saturation:

- If $x < x_l$ → 2D interpolation in the liquid region
- Otherwise, the quality of the two-phase conditions shall be determined using Eq. 1 and 2 and iterating in pressure

Now, for the reverse interpolation, P = f(x,y), where "x" can be ρ or s and "y" can be h, u or T:

- If x=ρ AND $x > x_{melting}$ OR x=s AND $x < x_{melting}$ → two-phase (solid-liquid) conditions. Quality shall be determined according to Eq. 1 and 2 and iterating in pressure
- A critical limit (y_{crit}) at the current x value shall be interpolated in the critical pressure curve:
  - If $y > y_{crit}$ → 2D interpolation in the supercritical region
  - Otherwise, a two-phase limit (y_g or y_l depending on the position of x regarding the critical point) shall be interpolated using the current value of property x:
    - If $x > y_g$ AND $x > x_{crit}$ → 2D interpolation in the superheated vapour region
    - If $x > y_l$ AND $x < x_{crit}$ → 2D interpolation in the liquid region
    - Otherwise, the quality of the two-phase conditions shall be determined using Eq. 1 and 2 and iterating in pressure

It is important to highlight the following:

- The relations "$x > x_g$" are reversed if x = density
- At P < Ptriple and two-phase flow, the vapour phase is extrapolated at T = Ttriple assuming ideal gas or using the real gas properties at the current pressure. Liquid phase is assumed to be frozen at Ttriple.
- Solid properties assume monotonous increasing melting line slope to work properly (increasing density and decreasing energy as the fluid becomes solid); otherwise the detection of phases could be erroneous

Figure 1 shows an H-S diagram with the different thermodynamic regions that ESPSS can manage automatically (circles in blue background). The solidification line and the new solid-liquid region are also included. Numbers in circles indicate the regions outside the range of available data, associated to the errors issued in case the simulation enters there.

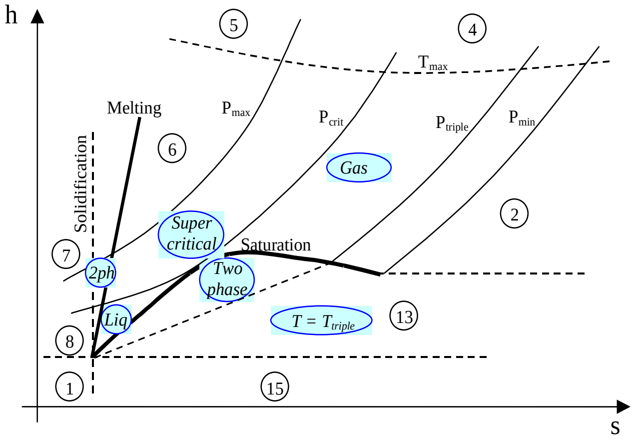

Figure 5 *H-S diagram*

Handling of errors

The control and handling of special situations is essential in order to avoid unexpected errors during the interpolation of properties and to reduce non-convergence issues. The implementation of the new range of properties covering the solidification zone made it necessary to update the detection of errors and special situations.

The most relevant potential issues to consider are summarized below:

- Properties not existing or in bad format: it is necessary to manage the reading of properties and assure the correct continuation of the program execution when solid properties don't exist or are in a non-compatible format; if this happens, the solid properties reading and interpolation are dismissed
- Different number of property points in the solidification line and the melting line: for the two-phase interpolation to work properly it is necessary to use the same number of points on both curves; this is achieved automatically by setting one of the lines as reference for the number of points and interpolating the other to obtain the properties at the same positions
- Extrapolation in property tables: the detection of extrapolation is different now since the range of properties is extended; it is no longer needed when the fluid enters the two-phase solid-liquid region and it is forbidden to enter the solid region

Extension of the built-in database

The FLUID_PROPERTIES library included in ESPSS contains the built-in database of fluid properties. It collects the most common fluids used in space propulsion, in different categories (real properties, perfect liquids, perfect gases and user-defined fluids) and ranging usually from the melting line to supercritical conditions.

In order to consider the slush state of fluids, the user has to incorporate the fluid properties along the solidification line to the real fluid properties files. These new data are added at the end of the file within a specific format.

It is possible to add the solidification line to any of the existing real fluid properties files using as many points as desired as long as the format is respected. This extended capability maintains backward compatibility in case the properties along the solid line are not provided.

It is important to mention that these lines are optional, which means that they will be used if they are included in the file, but the properties will work as usual if they are not present.

Adaptation of components and functions

The extension of properties into the slush state, as implemented in the properties database and in the interpolating functions, needed some small upgrades at EcosimPro Language level, both in the thermodynamic functions and in the components.

The code and in particular the functions interfaces, were unchanged as much as possible in order to reduce the non-compatibilities with previous versions.

With respect to the thermodynamic functions, there are three main upgrades to the "FL_state_vs_ru" function (thermodynamic state as function of density and internal energy):

- A new output argument has been added accounting for the solid phase mass fraction in the fluid, x_s. This variable is retrieved through the external library function "thermo_table_interp".
- The new state "slush" has been added to the enumerate list of available fluid states
- For the particular case when the same control volume contains a mixture of non-condensable gas and a main fluid in two-phase conditions (solid-liquid), the procedure followed, contained inside a double loop in p and T, is:
    - Thermodynamic properties of the liquid are called, function of p and T: this function detects if solid phase exists
    - The solidification temperature and the liquid and solid enthalpies are calculated
    - Thermodynamic properties are recalled function of p and h to calculate mass fraction of solid
    - A recalculation of the mixture enthalpy is computed from the solid fraction:

$$h_f = x_s \cdot h_s + (1 - x_s) \cdot h_l \qquad \textit{Eq. 3}$$

A possible improvement for a more precise calculation would imply to create a new iterative branch, specific for this case.

Regarding components, the modifications are:

- The addition of the new variable accounting for the solid phase mass fraction, x_s, in pipes and volume components
- The modification of the call to the thermodynamic function in order to add the new argument

The model presented in *Figure 6* has been created to test the new slush capability. It consists of an oxygen tank at 20 bar and 60 K discharging to a 1 bar fluid network with an ambient temperature of 40 K.

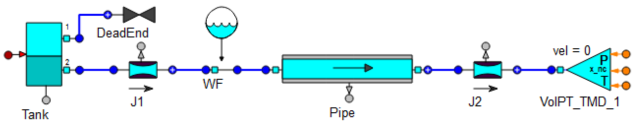

Figure 6 *Slush test case*

Figure 7 shows the results obtained for the slush mass fraction at the different pipe control volumes.

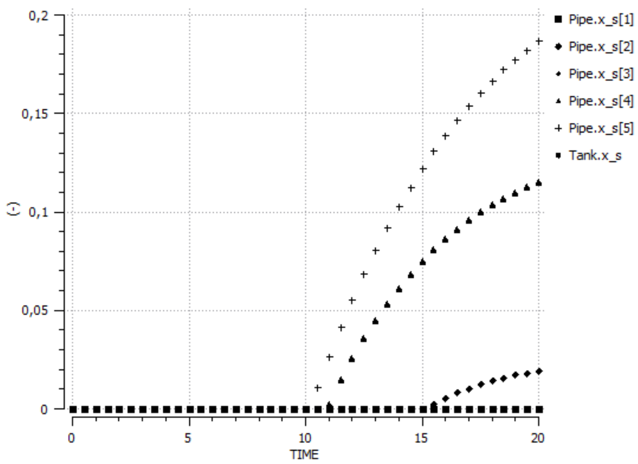

Figure 7 *Mass fraction results*

UPCOMING IMPROVEMENTS

As usual each year, a new release of the ESPSS toolkit is issued, which includes new features and general improvements. The most relevant currently being developed are the following:

- Improvements in the fluid friction correlation: the current friction model available in ESPSS, oriented to steady simulations, will be complemented by an unsteady model for transient simulations, aiming to improve the accuracy especially regarding cushioning of pressure waves
- Implementation of a sloshing model, to prepare for the coupling of ESPSS to GNC systems. Some of the tasks identified are:

- Analysis of the available literature to identify relevant sloshing models so that the implementations can be as generic and extendible as possible
- Rebuilding of the Frame component based on the continuous block and extension to non-rigid body terms
- Implementation of an equivalent sloshing model valid for perturbations around the quasi-steady configuration (pendulum model or similar)
- Extension of the simplified ESPSS tank model, including the calculation of the centre of mass and moment of inertia (quasi-steady)

ECOSIMPRO UPGRADES

As explained at the beginning of the article, a strong advantage of ESPSS is that the development of the platform and of the libraries goes in parallel. Some of the new features included in the latest version 5.10 of EcosimPro are:

- New multi-instance attribute editor for the schematics, enabling editing several objects simultaneously
- Importing/exporting of models using FMI standard improved to make it multi-process
- New transient solvers BACKEULER, BACKUELER_SPARSE (implicit fixed-step Euler) and RK45 (explicit variable-step Runge-Kutta-Fehlberg)
- New linear equations solver that speeds up simulations by up to 30%
- More real-time capabilities for monitoring all the integration steps of the simulation and detecting bottlenecks (graphic monitor of real-time compliance, optimized residues function, etc.)
- New matrix classes that allow matrix and vector arithmetic
- Improved Automatic Testing tool
- Improved HDF5 file comparer for navigating through the differences more quickly and intuitively
- Functions for converting real numbers to binary and hexadecimal
- Improvements to EDictionary and ESet containers to allow duplicates
- Improved exporting of models to MS Excel with external objects
- New management of page size and margins in schematics
- Improved graphic simulation monitor with more options for a more user-friendly experience
- Resolution of SPRs (software problem reports) detected in previous versions

CONCLUSIONS

ESPSS is a life project that feeds from the experience of a consortium of companies and institutions, including software developers and industrial users, in order to keep a state-of-the-art tool for the simulation of space propulsion systems.

Many items have been addressed over the development of the latest official version, among which one can emphasize:

- The inclusion of a model of a non-homogeneous two-phase pipe component
- The extension of the fluid properties to take into account slush phase

Future ESPSS releases will come in the near future thanks to the ongoing maintenance and development projects, following the path established in the past years. In addition, the developments implemented in the platform, EcosimPro, will cover the new requirements set out by the libraries.

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