SIMULATION OF THE COMPLETE ELECTRIC PROPULSION SYSTEM ASSOCIATED TO HET ON ESPSS/ECOSIMPRO

Jorge Ruiz-Torralba (1) (2), José Moral (2), F. Rodríguez (2), M. Aranda (2), J. Steelant (3), V. Fernández (3), M. Leonardi (4), F. Di Matteo (4)

(1) OHB System AG, Universitätsallee 27-29, 28359 Bremen. Email: jorge.ruiz@ohb.de
(2) Empresarios Agrupados Internacional. S.A., Magallanes 1, 28015 Madrid, Spain.
(3) ESA-ESTEC, Section of Flight Vehicles and Aerothermodynamics, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
(4) ESA-ESRIN, Section of VEGA & Space Rider Mechanical and Propulsion Engineering, Largo Galileo Galilei 1, 00024 Frascati, Italy

Abstract

This paper outlines the developments carried out in the Electric Propulsion (EP) library of the ESPSS toolkit (v3.6.0). It includes modelling enhancements applied to the electrical units of the Power Processing Unit (PPU) and the thermo-fluid control logic of the Fluid Management System (FMS).

The PPU is modelled using components of the standard electrical library, enabling a detailed modelling of electrical components as well as its direct connection with powerful power systems libraries on EcosimPro, such as ESA PEPS toolkit [1] and OHB EPS toolkit [2]. According to such electrical modelling standardization, the electrical units included in the thruster component are aligned for a proper compatibility. The FMS model simulates the thermodynamic evolution of xenon along storage tank, the Bang-Bang Pressure Regulator Unit (BPRU) and the Xenon Flow Controller (XFC). The foremost development is related to the control logic within BPRU, which determines the valves actuation based on the thermodynamic conditions at multiple components (in terms of pressure and temperature). This modelling assures the fulfillment of the demanding inlet conditions of the XFC in order to achieve an accurate flow control for the thruster.

Such library enhancements are shown by means of an application case corresponding to the complete propulsion system of SMART-1 mission [3]. This example showcases ESPSS capabilities to address interdisciplinary simulations, combining control, electrical, thermal and fluidic modelling.

1 Introduction

As part of ESA studies to address the upcoming trends in the field of electric propulsion, direct-drive architecture is foreseen as a key technology for more powerful EP solutions. This technology requires a high coupling between the satellite power system and the electric propulsion system. For such purpose, EcosimPro was identified as an ideal simulation platform due to its multidisciplinary [4]. This tool is the common platform used by the power section (PEPS toolkit [1]) and the propulsion section (ESPSS toolkit [5][6] [7]) of ESA for system analyses. To enable such coupled analyses, the Electric Propulsion (EP) library of ESPSS is updated to be compatible with PEPS.

Taking advantage of the advanced capabilities of ESPSS to model thermo-fluid-control systems [8], EP library is also updated with more elaborated fluidic cases applied to the FMS. Both fields under upgrade are described in this paper. The library enhancements are illustrated by means of the application case of SMART-1 mission [3] [8].

2 Electrical components upgrade

The previous EP library of ESPSS (v3.4.0) used customized electrical ports not compatible with the standard electrical port of EcosimPro [9]. The main upgrade at electrical interfaces is related to the use of the standard electrical port of EcosimPro in the EP library of ESPSS v3.6.0. These changes mainly apply to the PPU and thruster components.

2.1 Power Processing Unit

The former PPU component only modelled the electrical parameter of interest of the corresponding electric unit. For those units controlled by voltage sources (anode, ignition keeper, valves and acceleration grid, shown in Figure 1), the voltage was set according to the corresponding operational mode, but the current was not modelled. For those units controlled by current sources (magnet, heater and thermothrottle, shown in Figure 1), only current values were modelled. Besides, these voltage and current values were transferred to the ports via source code to avoid the non-desired boundary conditions (in case of using the standard electrical port).

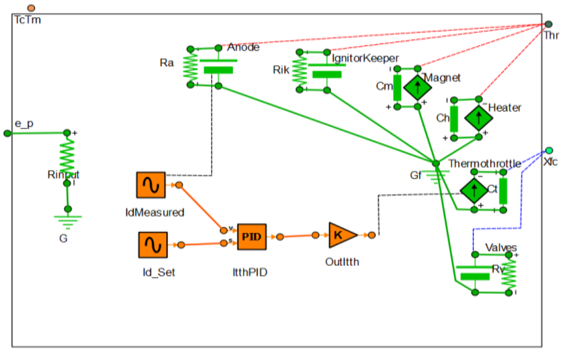

Figure 1: PPU component on ESPSS v3.4.0 [9]

The new PPU component (see Figure 2) does model both voltage and current for each electric unit, as it is required by the standard electrical port. For those units controlled by voltage sources, the operational voltage is set by the PPU, meanwhile the operational current is determined by the connected components by means of Ohm's law. For those units controlled by current sources, the operational voltage is determined by the connected component using Ohm's law as well. Notice that the source code shown in Figure 2 is different to the PPU symbol used in Figure 6, but it represents the same component.

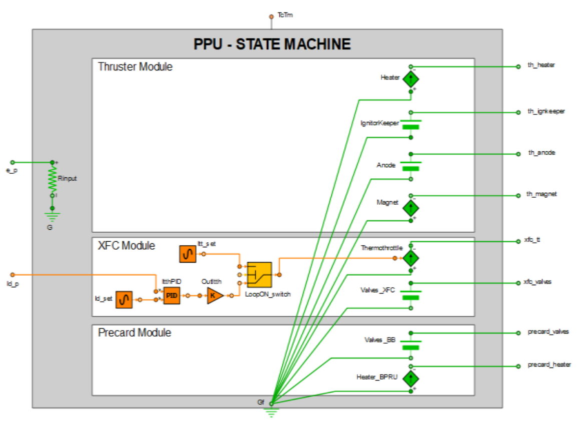

Figure 2: PPU source code on ESPSS v3.6.0

Aiming to a better understanding for the user, the control logic is also modified using components of the standard control library (orange and yellow components in Figure 2). First, the signal measured from the thruster (discharge current) is modelled using a control port connected to the thruster component. Second, a switch component is used to graphically distinguish between the two control-logic options of the thruster discharge current: one is based on directly setting its value via tele-command and another is based on a PID control.

2.2 Thruster

The upgraded thruster component includes an individual electrical port per electrical unit (an individual one for the heater, the ignitor, the anode and the magnet), as it is shown in Figure 3 by the green ports. The blue port represents the fluid inlet, meanwhile the orange port is a control-information port that provides as output the operational discharge current of the thruster.

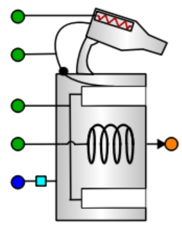

Figure 3: EP thruster symbol on ESPSS v3.6.0

So as to model the electrical performance of each unit, Ohm's law is applied to determine the electric parameter that is not directly set by the PPU:

$$V_{heater} = I_{heater} \cdot R_{heater} \quad (1)$$

$$V_{magnet} = I_{magnet} \cdot R_{magnet} \quad (2)$$

$$V_{ign,keep} = I_{ign,keep} \cdot R_{ign,keep} \quad (3)$$

Notice that the discharge current (I_d) is not calculated by Ohm's law, the discharge current is an output performance parameter based on the plasma behavior within the thruster. It is determined as function of the inlet mass flow, which is proportional to the discharge current triggered by the ionization process within the thruster.

$$I_d = \dot{m}/k_I \quad (4)$$

where k_I *[kg/s/A]* is a constant parameter of the thruster. Finally, the total power consumed by the thruster is computed according to the electrical performance of each unit.

3 Fluidic components upgrade

3.1 Bang-Bang control logic

PrecardBB is a new component of EP library v3.6.0 (see Figure 4). This component controls the performance of the Bang-Bang Pressure Regulator Unit

(BPRU) by means of a closed-control loop. The most important features are the following:

- The actuation of Bang-Bang valves is controlled according to the pressure conditions at the tank, the inter-cavity (volume between Bang-Bang valves) and the plenum (volume downstream of the second Bang-Bang valve).
- A thermal control is included to operate the BPRU within a configurable temperature range. For such purpose, a heater is operated in switch on-off mode depending on the plate temperature where the BPRU is attached.

Aiming to a better understanding and use of the component, the symbol includes multiple labels to easily identify each port (see Figure 4).

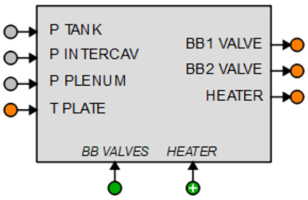

Figure 4: PrecardBB symbol on ESPSS v3.6.0

PrecardBB receives the instantaneous pressure of the tank (P_{tank}), the inter-cavity ($P_{inter-cav}$) and the plenum (P_{plenum}). This information comes from the sensor ports of the aforementioned components, represented in grey color and identified with intuitive names in Figure 4. These pressure inputs are used by the component to evaluate the current status of these components and, according to it, to determine the valves actuation as follows:

- <u>BB1 valve (upstream bang-bang valve):</u> it is activated when the plenum pressure is smaller than the minimum configured pressure (input data) and it is closed when $P_{inter-cav} = 0.99 \cdot P_{tank}$.
- <u>BB2 valve (downstream bang-bang valve):</u> it is opened after the BB1 valve closing plus a set waiting time (input data). The closure is commanded when $P_{inter-cav} = 1.001 \cdot P_{plenum}$ or when the maximum pressure at the plenum is reached (input data of PrecardBB component).

This control logic is easily implemented on EcosimPro language within the discrete block. This component also models the thermal control of the BPRU according to upper and lower temperature limits set by the user in the input data of the component. This component receives the instantaneous reference temperature via the left orange port, labelled as T_{PLATE} in Figure 4. The green ports in the bottom part of Figure 4 represent the electrical interfaces of the pre-card with the PPU. The orange right ports represent control ports to command the activation or deactivation of the bang-bang valves and heater.

3.2 Xenon Flow Controller (XFC)

The XFC component determines the mass flow injected into the thruster as function the device core temperature, the inlet pressure and the thermothrottle current imposed by the PPU. This model is derived from correlations based on characteristic performance curves from experiments [5]. This approach is followed because the detailed design of this component requires too many input data, which are only available in-house of the device manufacturer. Note that this component can be fully customized by the user according to the device under consideration. It is worth pointing out that ESPSS also offers optimum capabilities for the detailed design of this fluidic unit, enabling to couple thermal, control, electrical and fluidic modelling. Reference [10] is an ideal showcase of ESPSS capabilities.

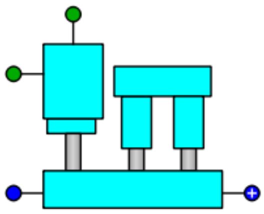

Figure 5: XFC symbol on ESPSS v3.6.0

The blue ports model the fluidic inlet and outlet, meanwhile the green ports are related to electrical modelling. One corresponds to the XFC valves and the other to the thermothrottle current controlled by the PPU.

4 SMART-1 application case

Figure 6 shows the propulsion system of SMART-1 on ESPSS, including the fluid management subsystem, the power processing unit and the plasma thruster. Blue connections are related to fluid modelling, red connections to thermal modelling, green connections to electrical interfaces and orange connections are related to control modelling. This model is based on the SMART-1 system published by Iberespacio [3] along with the further developments carried out by Ruiz et al. [11].

The fluid management sub-system simulates the xenon evolution, by means of real fluid formulation, through the storage tank, the Bang-Bang Pressure Regulator Unit (BPRU) and Xenon Flow Controller (XFC). The conductive and radiative heat exchange between the BPRU components and the environment is modelled by the upper thermal mesh (com-

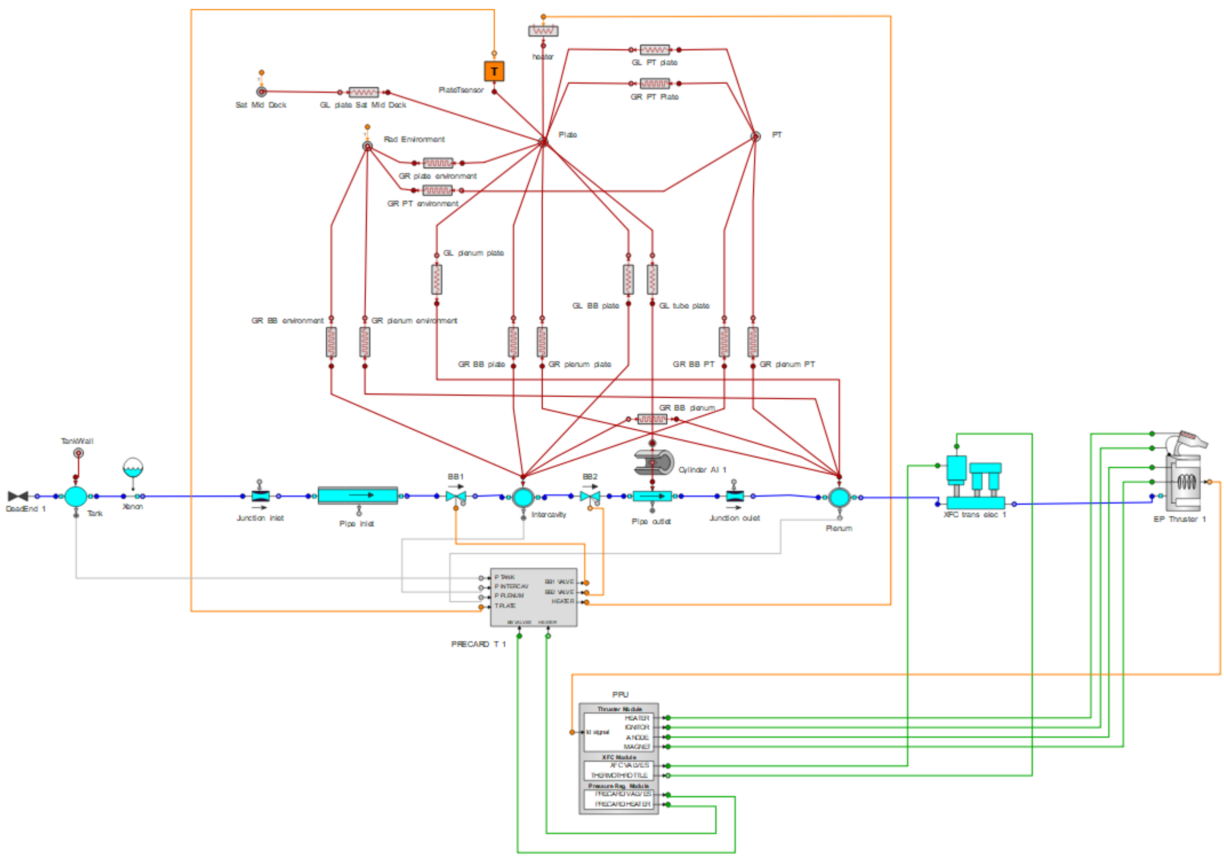

Figure 6: SMART-1 Propulsion System model on ESPSS

ponents connected by red connections). The XFC determines accurately the mass flow rate injected into the thruster by means of capillary tubes. So as to fulfil such demanding requirements, the xenon is provided to the XFC under specific thermodynamic conditions from the BRPU, pressure within [1.99, 2.01] bar and temperature within [25, 27] ºC. These settings are inputs to the PrecardBB component via an attribute editor.

The thruster used in the model is the PPS1350. The model applies a set of tables for the performance characteristics taken from the bibliography [5]. On the other side, the discharge voltage imposed by the PPU is 300V. The pre-treatment time of the system up to the first ignition is set to 100s. The control option of the PPU for the discharge current is set to PID control. This option reads the operational discharge current (I_d) of the thruster via the control-orange port connecting the thruster and the PPU (see Figure 6). The measured I_d is transferred to the PID controller of the PPU (shown in Figure 2). According to the measured and commanded discharge current, the PID controller modifies the thermothrottle current of the XFC until reaching the commanded one. This is achieved by means of modifying the injected mass flow into the thruster by means of the thermothrottle current, since the discharge current is proportional to the mass flow (see Equation 4). The following discharge currents are commanded along the simulation case: Id = 5 A from 0 to 250s, Id = 4.5 A from 250 to 500s, Id = 4 A from 500 to 750s and Id = 3.5 A from 750 to 1200s.

As it is shown in Figure 7, the BPRU keeps the plenum pressure within the pressure operational limits established by the pre-card (between 1.99±5% bar and 2.01±5% bar).

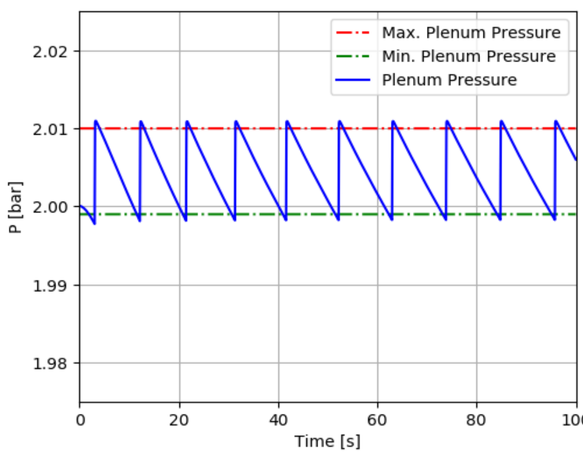

Figure 7: Pressure evolution of the plenum along multiple bang-bang sequences

The valves actuation sequence is in line with the pre-card control logic, as it shown in Figure 8. BB1 valve is activated when the plenum pressure is smaller than minimum set pressure (top graph) and

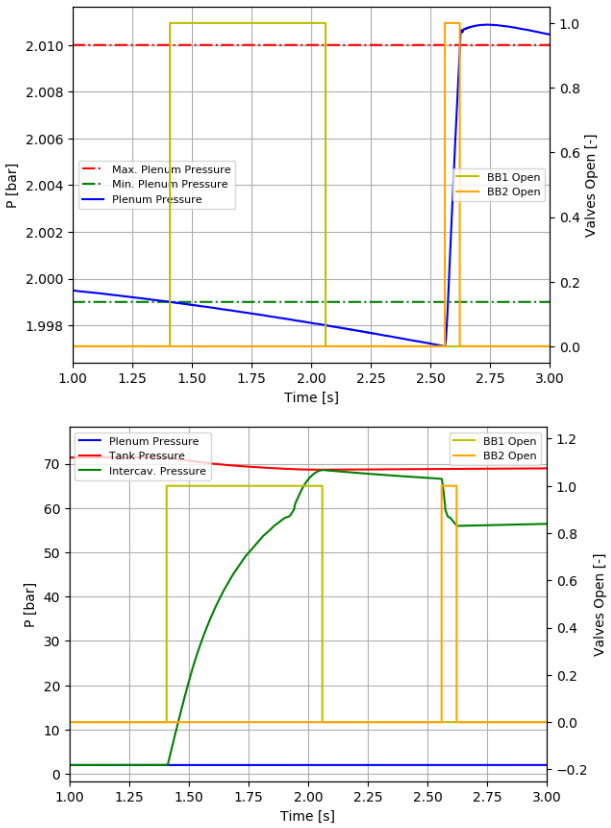

Figure 8: Valves actuation in a single bang-bang sequence

it is closed when the pressure of the inter-cavity matches with tank pressure (bottom graph). BB2 valve is opened after the BB1 valve closure plus the-set waiting time (0.5s), in order to isolate the tank and the plenum. The BB2 valve deactivation is triggered when the maximum pressure of the plenum is reached (2.01 bar), as it is illustrated by the top graph of Figure 8. Notice that in this case, the condition of closing BB2 due to the inter-cavity pressure matching with plenum pressure is not applicable, since the system is at beginning of life and the tank pressure is the greatest one.

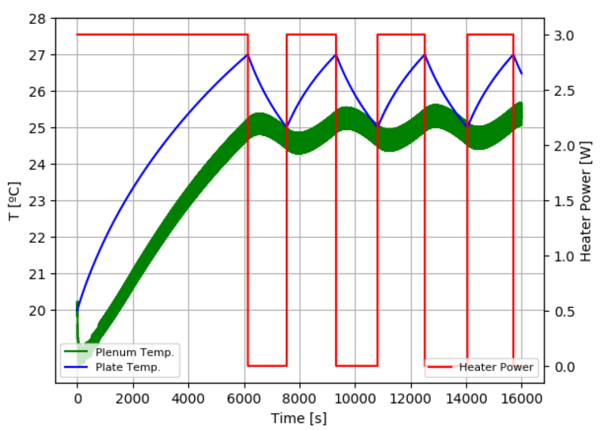

Figure 9: Thermal control of BPRU plate

In the long-term analysis, the operational temperature limits of the plate (between 25ºC and 27ºC) are properly controlled by the activation/deactivation of the plate heater (see Figure 9).

Figure 10 illustrates the control logic of the PID controller to achieve the commanded discharge currents along simulation. The time period from 0-100s corresponds to the ignition time, for that reason the discharge current and the thermothrottle current are null. The PID controller actuates over the thermothrottle of XFC to control the discharge current of the thruster. The thermothrottle current controlled by the PID increases to reduce the discharge current.

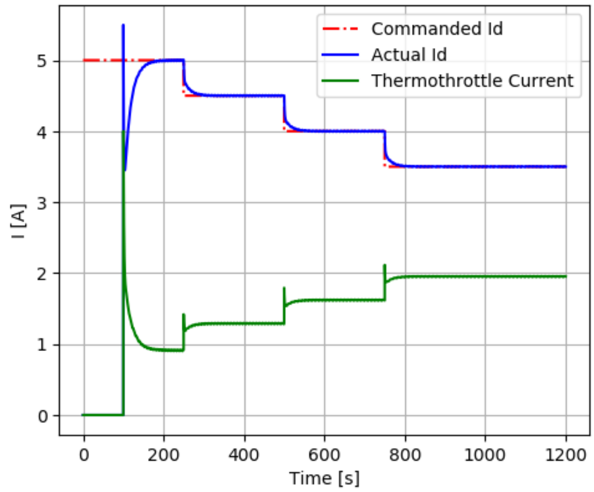

Figure 10: Control of the discharge current by means of the thermothrottle current

The increase of the thermothrottle current heats up the fluid and decreases its density, resulting in a lower mass flow through the XFC, as it is shown by Figure 11. The thrust decreases with the mass flow, as it is seen in Figure 12.

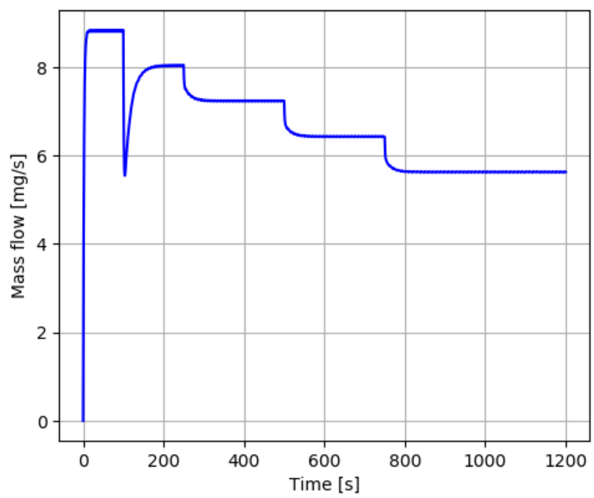

Figure 11: Mass flow evolution

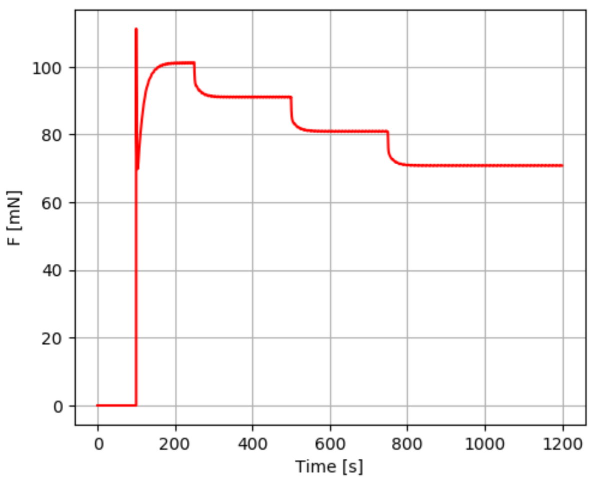

Figure 12: Thrust evolution

5 Conclusions

The two foremost goals of this paper are fulfilled. First, the EP library of ESPSS is updated to enable coupled simulations between the satellite power system and the electric propulsion system. In particular, coupled simulation at system level between ESPSS toolkit and PEPS toolkit at ESA. This paves the way to address the upcoming trends in the field of electric propulsion, especially for direct-drive architectures.

Second, the ESPSS capabilities for modelling the fluid management system of EP systems are showcased by means of the simulation of the complete propulsion system of SMART-1 mission. This system simulation combines multiple modelling areas (electrical, thermal, fluid and control), enabling a complete understanding of the interdependency existing between all sub-systems and their influence over the whole system performance. In addition, ESPSS is proposed as a suitable simulation platform to address the design of the fluid management system of alternative propellants for EP and cubesats.

6 Acknowledgement

This paper describes the first task that I carried out on EcosimPro/ESPSS as part of my bachelor's (2016) and master's thesis at EAI (2018). It opened me the door to the thrilling world of simulation with EcosimPro/ESPSS, which I enjoy every single day at my job. Without this application case, I would have never worked in the propulsion field.

Thanks to ESA people who allowed me to integrate my master's thesis on ESPSS. Many thanks to all EAI colleagues who helped me and supported me on this road (Javier, Pedro, Ángel, Fernando and many more). But especially millions of thanks to José Moral, who spent countless hours to transmit me his highly valuable knowledge. Every single line of code and task that I do is thanks to your patience, your humility, your kindness and your curiosity. I learned from you most of the things that I know, not only at technical standpoint, but also at personal standpoint. Pepe, I thank you more than words can say.

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