SPACE PROPULSION 2020
ESTORIL, PORTUGAL / 08 – 12 FEBRUARY 2020

VALIDATION OF A XENON PROPULSION SYSTEM SIMULATION MODEL WITH 5-KW CLASS HALL-EFFECT THRUSTER COUPLED TESTS

Patrick Fleith [(1)], Andrea Leporini [(1)], Romain Fafet [(2)] Michele Coletti [(3)]

[(1)] Thales Alenia Space in the UK, Curie Avenue, Harwell Oxford, OX11 0RH, UK
[(2)]Thales Alenia Space in France, 5 Alles des Gabians, Cannes, 06150, France
romain.fafet@thalesaleniaspace.com
[(3)] Thales Alenia Space in the UK, Curie Avenue, Harwell Oxford, OX11 0RH, UK
michele.coletti@thalesaleniaspace.com

KEYWORDS: Hall-effect thruster, Coupled-tests, fluidic model validation, EcosimPro, transient analysis.

ABSTRACT:

This paper compares the coupled test results of a 5 kW-class Hall-Effect Thruster (HET) to the simulation results of a complete Xenon Propulsion System (XPS) model.

The simulator has been set up in EcosimPro software. It includes detailed component models of the fluidic lines, a pressure regulation assembly, a Power Processing Unit, a Flow Control Unit and a Hall-Effect Thruster. Component features originate from their specification, design, and/or elementary tests.

In this paper we discuss the validation of the integrated XPS simulator by comparing the simulation results with coupled tests that have been carried out with flight-representative hardware. In particular, we show excellent correlation of transient behaviours (i.e, at start-up, during transition between operating set points) and steady-state performances. Selected metrics are discharge current and thermothrottle current commanded for thrust regulation, and time constant of transition between operating points. This provides high-level of confidence and credibility of the model for simulation of a wide range of operational scenarios.

1. INTRODUCTION

The primary motivation behind the development of an XPS simulator is to simulate steady-state performances and to carry out transient analyses during thruster start up and transitions between operating points. Tracked parameters are discharge current, thermothrottle current commanded for thrust regulation, and time constant of transition between operating points. The simulator aims to be well-adapted to represent transient phenomenon with a timescale between 0.1s and 1000s. 0.1s correspond to the frequency of the PPU control law. Shorter phenomena such as inrush current, thruster single events, discharge current oscillation are not modelled. More generally, electrical or plasma phenomena are not reproduced by the simulator hence thrust and Isp performances are based on thruster performance maps. Also simulations longer than 1000s are not practical because of the long computing time.

In this paper the EcosimPro model will be presented and its main components described. The model will then be compared to the results of a sub-system coupling test to verify its performances and validate its ability to be used as a simulation tool.

2. PROPULSION SUBSYSTEM DESCRIPTION

The hall-effect (HET) based xenon propulsion subsystem contains, among others, the following equipment:

- An high pressure section with multiple tanks: which provide high pressure xenon to the pressure regulator assembly;
- A pressure regulator assembly which contains Latch valves, pressure regulators and particle filter;
- Power Processing Units (PPU);
- Xenon Flow Controllers (XFC);
- Hall-Effect Thrusters;
- Fluidic tubework.

A typical schematic of a xenon propulsion system under production in TAS can be seen in [1].
Each of the equipment reported above is modelled individually and later integrated in an overall subsystem model.
A description of each of the models is presented in the sections below.

3. EQUIPMENT MODELS

Individual equipment have been modelled with attributes originating from their specifications, their designs, and/or through elementary tests. Such models are reported below.

3.1. Fluidic lines

Tube, tees and Tanks are standard components from the EcosimPro FLUID_FLOW_1D library. The tubing properties (e.g. inner diameter, surface roughness of the pipe wall, materials properties, length, bends geometry) are taken from high-fidelity CAD models of the fluidic lines.

Elbows, and restriction components are also based on the junction component from the FLUID_FLOW_1D library with a custom pressure drop. Such pressure drops have been widely characterized by TAS in the frame of past developments of chemical propulsion system and the same data re re-used here.

3.2. Latch Valve Model

The latch valve is a standard Valve component from the FLUID_FLOW_1D library. Its orifice area has been adjusted such as the calculated pressure drop matches the valve qualification test results performed with helium (see Figure 1).

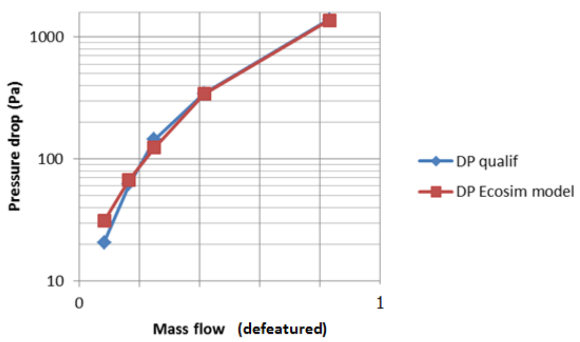


Figure 1 – Pressure drop curve for latch valve

3.3. Filter Model

The filter is a standard component from the EcosimPro standard's FLUID_FLOW_1D library. The pressure drop measured during the filter qualification is directly taken for the reference pressure drop in the filter component settings.

3.4. Pressure Regulator Model

The regulated pressure depends on various parameters including manufacturing dispersion, temperature, mass flow, inlet pressure, etc.

The model is based off the standard EcosimPro regulator component with a custom valve opening function and the pressure drop of the outlet filter.

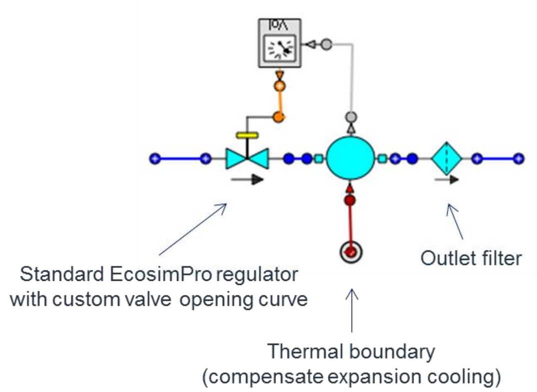


Figure 2 - Pressure Regulator model representation in EcosimPro

The mass flow and the inlet pressure vary during a simulation. Their effect on the regulated pressure has been characterized during a qualification test and an attempt has been done to include this in the EcosimPro model. However given the complex effect between selected pressure setpoint, mass flow rate and input pressure over the regulator outlet pressure accuracy it has been decided to leave this as a user defined parameter to allow the simulation of worst case scenarios where the pressure can be set to the maximum (or minimum) allowable value.
In line with this the dynamics response of the regulator has not been extensively modelled.

3.5. Xenon Flow Controller Model

The XFC provided by the thruster supplier has the aim of regulating the mass flow rate to the thruster and is controlled in closed loop by the PPU.
The XFC acts on the viscosity of the Xenon flow by flowing current (thermothrottle current I_{tt}) along a capillary tube (consequently heating it up) through which the Xe flow passes hence producing higher or lower pressure drops ultimately changing the Xe flow rate.
The thermothrottle dynamics is modelled as a 1st order low pass filter on the square of the thermothrottle current (proportional to the power).

$$\tau \dot{I_{eq}}^2 + I_{eq}^2 = I_{tt}^2 \qquad \text{Eq. 1}$$

I_{tt} is the commanded thermothrottle current, I_{eq} is the equivalent thermothrottle current used for computation of the actual mass flow with XFC dynamics, and τ is the time constant of the 1st order low pass filter. This time constant has been correlated with experimental data as shown by the mass flow response vs steps of thermothrottle current (see Figure 3).

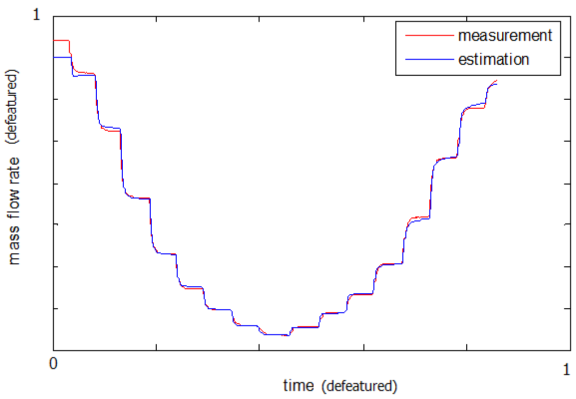


Figure 3. XFC dynamics correlation

The mass flow law is then computed as a function of the inputs (thermothrottle current, XFC temperature reference point, and inlet pressure) based on empirical formula derived by fitting experimental data and normally having an accuracy of the order of 2%. The mass flow is then distributed to the anode and the cathode in a fixed ratio in line with what is reported by the supplier.

Finally the internal XFC valves dynamics is also modelled as a 1st order low pass filter to correctly simulate the valve opening and shut off time.

3.6. Hall-Effect Thruster Model

As reported above the model does not take into account any plasma physics effect, For this reason the HET model is a strong simplification of reality. Nevertheless as will be presented in the next sections the results of the model are still good enough to represent the overall subsystem dynamic.
The thruster model assumes an instantaneous change of the performances in reaction to the modification of input parameters (mass flow and discharge voltage).
The inside the HET model a “transfer function” to convert the mass flow rate regulated by the XFC into discharge current is present. Such function is representative of a family average beginning of life (BOL) HET of those employed on TAS SBNEO platform.

3.7. PPU

Finally, the PPU is modelled from the information available in the user manual and was validated by peer-review of the code. All electrical supplies are represented as ideal current or voltage sources, except for the anode supply that simulates the power limitation mode (see Figure 4).
The EcosimPro model reproduces the startup sequence and the setpoint regulation of a real PPU with the same settings.
The PPU reads the discharge current and the thermothrottle current command is calculated with a PI controller representative of the one integrated in the flight model. Also, a bias on the discharge current measurement can be set by the model user for worst cases transient analyses.

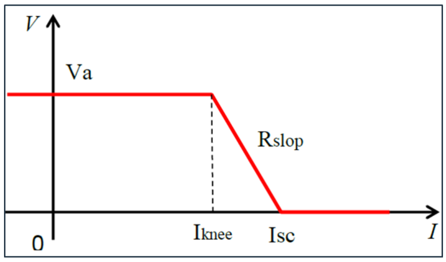


Figure 4. Anode supplied voltage and knee current

4. HET COUPLED TEST MODEL SETUP

The simulations performed with the fluidic model in EcosimPro (shown by Figure 5) were compared to the experimental results acquired during one of the coupling test carried out with a representative S/S configuration during the subsystem development phase.

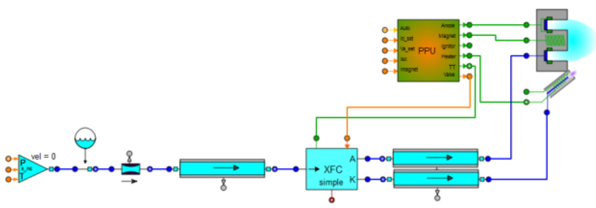


Figure 5. EcosimPro schematic model of the HET coupled test setup

PPU:
The coupling test was carried out with a flight representative PPU and with flight representative settings. The same settings were implemented in the EcosimPro simulation, and no noise or bias on the discharge current measurement was introduced.

XFC:
The data from a steady-state mass flow characterization of the actual XFC serial number used in the test were used to define the mass flow law implemented into the model, which had the same formulation of the one described in Sec. 3.5 but with updated coefficient to provide an RMS error of 1% with respect to the tested XFC.
Finally, the temperature measured during the test on the XFC reference point (XFC TRP) was taken as a boundary condition since the EcosimPro model does not have the goal of thermally simulating the XPS subsystem.
The regulated pressure measured during the test is set as the boundary condition since the test bench pressure regulator is not a modelled component.

Tubing: The actual length and tubing setup (tees, elbows etc) during the coupled test was implemented into the model.

Timing: The time of the thruster ignition have been synchronized between the simulation and the test data to facilitate transient behaviours comparison.

5. MODEL VALIDATION

5.1. Sequence S1 (nominal case)

First the model was compared to sequence S1 which represent the nominal operation of the subsystem and scans through the nominal flight setpoint (ignition, orbit raising EOR and station keeping ESK). It must be noted that in this test the pressure is regulated to its nominal value whereas the XFC temperature reference point (TRP) varies significantly during the test ($\Delta T = 30°C$).

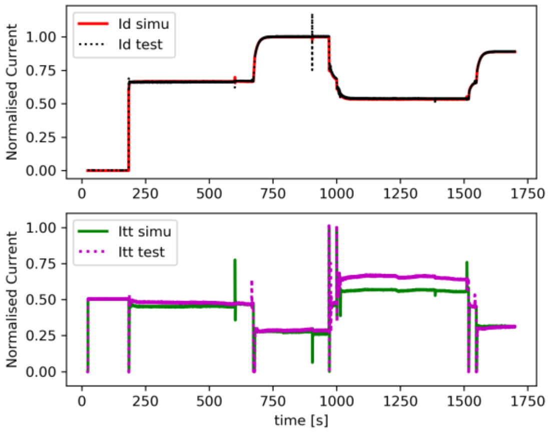


Figure 6 – Comparison of test vs simulated discharge current and thermothrottle current for S1 sequence (nominal).

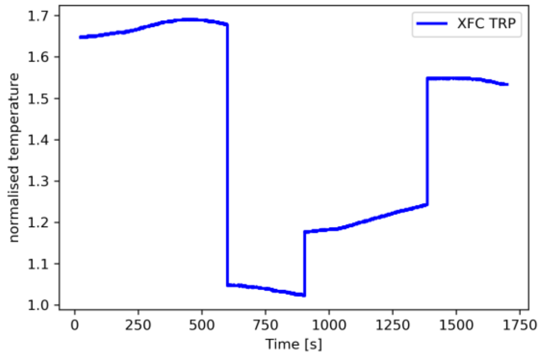


Figure 7 - XFC temperature boundary condition for simulation.

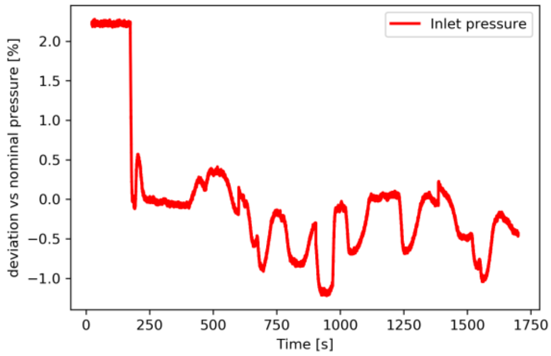


Figure 8 – Inlet pressure deviation used for simulation upstream boundary condition vs nominal regulated pressure.

A comparison between the simulation and the experimental results is presented in Figure 6 – Figure 8. Overall the simulation is in very good agreement with the experiment however some discrepancies can be observed and these are presented below.

In Figure 6 some current peaks can be observed in discharge current (Id) and thermothrottle current (Itt). These are artefacts due to abrupt change in simulation boundary conditions imposed from test data measurement of inlet pressure and XFC TRP due to the fact that test data used for boundary conditions have been cut-off to save simulation time. For example the jump in temperature seen at ~580s, ~900s and 1350s in Figure 7 are where the experimental data are “cut” and in fact when this happens peaks in Itt (and in Id) can be seen since the simulated control loop is adapting to this abrupt change in XFC TRP.

For what concerns the discharge current a steady state bias smaller than +/-0.6 % can be observed between numerical and experimental data. This is consistent with the values of the overall experimental command and acquisition chain and hence is an extremely good result.

On Figure 6, we can see that there is a difference in the average thermothrottle current measured during the test and the value calculated by the simulation. The difference is particularly important for the station keeping operating point (between 1000 and 1500s s). In fact the simulation underestimated the steady-state thermothrottle current by 14%.

This difference can be caused by various dispersions:

- Thruster performance dispersion in the relationship between mass flow rate and discharge current of the HET used during the test
- Uncertainties when interpolating the XFC performances between characterisation points.

- Sensor bias during the coupled test (XFC temperature, pressure).

According to Figure 9, the mass flow measured during the test is 7% lower than in the simulation. Considering that the XFC model has been tuned to the particular XFC used and that both the test and the model the PPU control loop aims at keeping a constant discharge current a major contributor to this error is expected to be the thruster performance.

This difference is not surprising considering the variation of thruster to thruster performance and noting that, as reported above the HET model using in the simulation has not been tuned to the particular HET serial number used in the test.

Moreover, the oscillations that can be seen on the measured mass flow rate are an “artefact” of the coupled test setup due to the position of the mass flow sensor (too close to the pressure regulation valve). Such mas flow oscillations are clearly not present at the thruster inlet otherwise they would have been seen either in the experimental Itt trace (since the PPU loop will tend to compensate them commanding the Itt) or in the Id trace (if the Itt cannot compensate it).

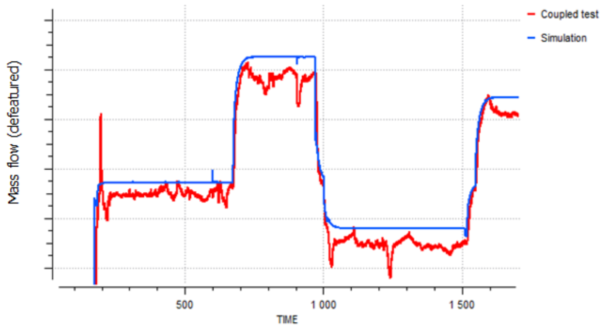


Figure 9 - Comparison of simulated and measured mass flow in S1

A comparison showing the transition from the HET start-up to orbit raising operating point is shown in the next figures

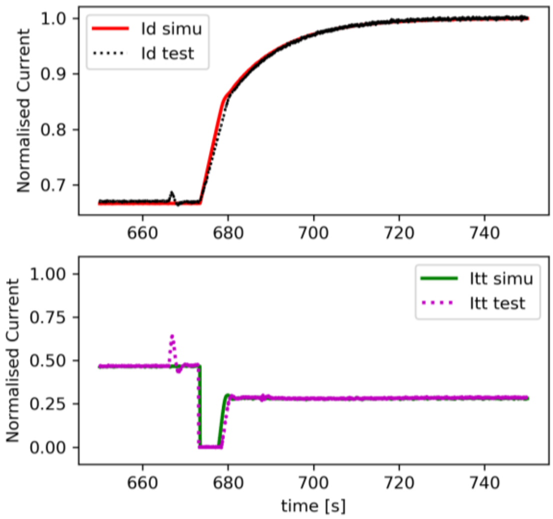


Figure 10 - Transient from startup to orbit raising operating point.

From T=673s to T=680s, during the saturation of Itt, the slope of Id is lower in the simulation. For this transition, the thermothrottle time constant seems to be slightly greater than what is used for the simulation. Nevertheless the numerical to experimental data comparison is more than satisfactory

The duration of the transition is correctly predicted with an absolute error below 1s.

The comparison for the transition from orbit raising operating point to low-power operating mode is instead reported in Figure 11.

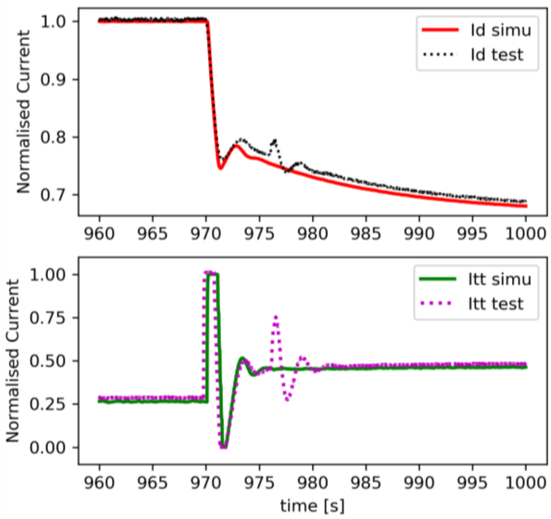


Figure 11 – Transient from orbit raising to low-power operating point.

The experimental data show 2 full oscillation cycles of the thermothrottle current whereas the simulation only show at the set point change at t=970s.

The Itt oscillation in the experimental data are caused by a change in magnet current which is part of the sequence required to change the

setpoint.
In reality the change of magnet current changes the plasma properties causing a change in Id to which the Itt reacts. The simulator instead, not being able to predict any plasma physics behaviour cannot understand the effect of a magnet current change and therefore does not see the discharge current peak hence not causing and Itt reaction.
Anyway the duration of the transition is correctly predicted with an absolute error of 2.7s which is considered acceptable

5.1.1 Start-up comparison

In this section we take a closer look at the simulated start-up vs coupled test data.

As expected, the inrush current is visible in the test but not in the simulation (see Figure 12). To do so, the coupling between the PU electronics and the plasma resistance at ignition would have to be simulated. The discharge current immediately after the inrush current is correctly predicted.
Also a delay in Itt can be observed between the test and the simulation. However this delay is only of about 0.3seconds and can be imputed to the different response time between the real PPU and the simulator. Apart from this the Itt response is remarkably close between experimental and numerical data with the test showing a slightly higher peak in Itt than the simulation.

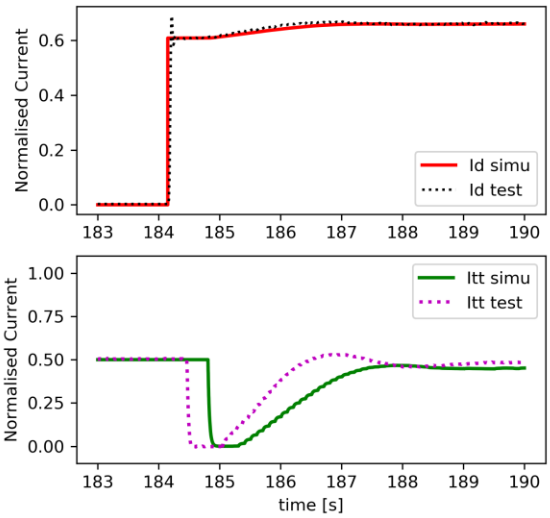


Figure 12 – Discharge and thermothrottle currents comparison between simulation and coupled tests for S1 start-up.

5.2. Sequence S2 (hot XFC, low-pressure case)

The firing sequence S2 is representative of the EOR case resulting in the minimum thermothrottle current and is characterized by:

- Maximum mass flow demand at thruster inlet (startup OP, then orbit raising OP).
- Hot XFC, i.e. max allowable temperatures (increasing flow xenon viscosity, thus reducing flow);
- Minimum regulated pressure (decreasing the mass flow).

As for S1 sequence, the simulation is globally in good agreement with the experiment. As already seen previously a steady-state difference on the thermothrottle current exists. As discussed, this can be imputed to the inaccuracy of the transfer function between mass flow rate and discharge current since the model was not tuned to the specific HET used in the coupling test.

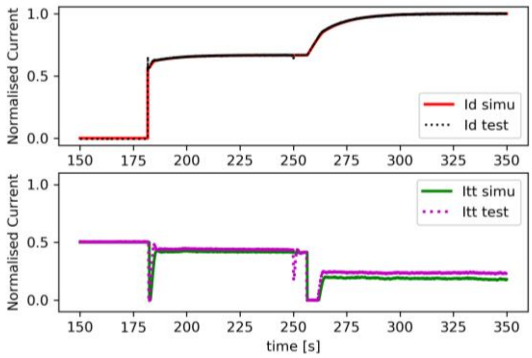
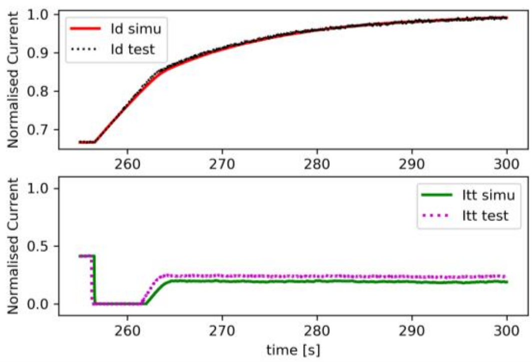


Figure 13 – Simulated vs coupled tests discharge and thermothrottle currents for firing S2.

The duration of the transition is predicted with an accuracy of 2% w.r.t. coupled tests which is again considered satisfactory.



For the operating point transition: the same comments as for 5.1 applies.

5.3. Sequence S3 (cold XFC, high-pressure case)

The firing sequence S3 represents the case of station keeping phase with worst case conditions for the maximum thermothrottle current and is characterized by.

- Maximum inlet pressure;
- Cold XFC (lowest allowed temperature);
- Minimum mass flow demand (startup OP, then station keeping OP).

The duration of the transition is predicted with an accuracy of 5.6% w.r.t. coupled tests which is considered acceptable.
As already seen in Sec. 5.1 and 5.2 the computed Itt value tends to underestimate the measured one. As before this is imputed to thruster to thruster variation and to the model not being fitted to the actual HET used during the tests

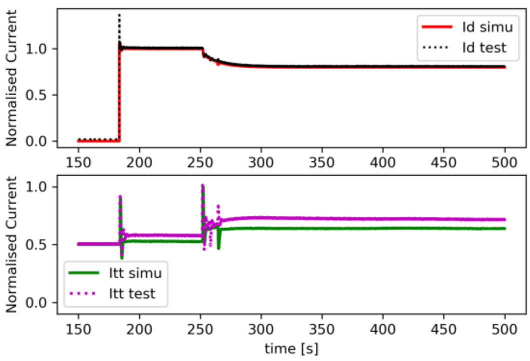


Figure 14 – Comparison of simulated and measured discharge and thermothrottle current in S3 (high-pressure, cold case).

As already discussed previously in Sec 5.1.1 the inrush current which can be seen at ignition cannot be represented by the simulator. Also, in this case a small delay between the simulated and measured Itt trace can be seen.

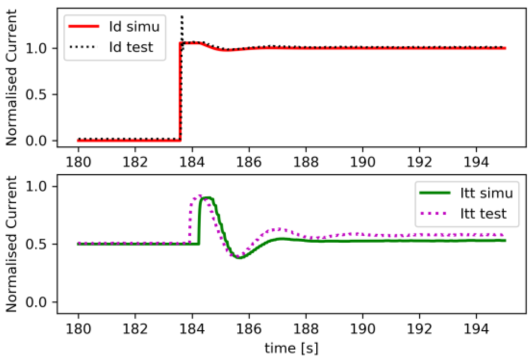


Figure 15 - Zoom at start-up comparison of simulated and measured discharge and thermothrottle currents for S3.

Finally as discussed in Sec. 5.1 two Itt oscillations can be seen on the experimental data and not on the numerical simulation. The first oscillation is relative to a change of the magnet current that is outside of the model capability. The second oscillation is instead due to the change in discharge voltage needed to achieve the ESK setpoint. As for the magnet current this causes a current transient due to a change in the plasma properties to which the PPU reacts modifying the Itt to maintain a constant discharge current.
EcosimPro, not being able to model the plasma response of the HET cannot predict this hence "neglects" this effect.

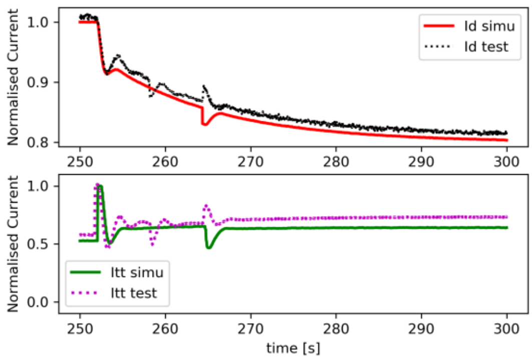


Figure 16 – Zoom on transition for comparison of discharge and thermothrottle currents for S3.

6. CONCLUSION

An EcosimPro model able to simulate the behaviour of an electric propulsion based subsystem utilizing 5-kW class HETs has been presented. Its comparison to experimental data collected during a coupling test has been used to validate its performances.
The model has shown the ability to correctly reproduce the discharge current and thermo-throttle current trends with the exception of being able to predict short term effect cause by magnet current or discharge voltage adaptation.
This was expected since the model does not include any plasma physics capability and it represents the thruster simply as a "transfer function" between mass flow rate and discharge current.
The steady state Itt value was found to be lower than the experimental measurement and this is most likely imputed to the fact that the transfer function used in the model is a "general" one valid for a BOL HET and has not been best fitted to the actual HET used during the test.
The overall setpoint transition time has also been predicted with errors of the order of 5% or less.
Overall the model validation is considered successful and provides good confidence for its used in the simulation of a wide range of operational scenarios.

7. ACKNOWLEDGMENT

The authors would like to express sincere acknowledgement to ESA and UK Space Agency for their invaluable support in the frame of the NEOSAT Partnership Project.

8. REFERENCES

1. M. Pollard et al., "Overview of spacecraft propulsion activities in Thales Alenia Space in the UK", SP2020_00339, Space Propulsion 2020, Estoril, Portugal, 8-12 February 2021