

# PPS®5000 Hall Thruster Unit with a Dynamic Mass flow rate Tool

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## Abstract

The 5-kW PPS®5000 Hall thruster is currently under qualification at Safran. The life test demonstration has exceeded the 12,800-hr milestone, with the thruster delivering a total impulse of almost 11.7 MN.s. In parallel to the ongoing qualification life test on the primary qualification unit, additional test campaigns are being conducted with other qualification-standard hardware. These parallel activities are in support of the qualification as risk-mitigation actions, or as system-compatibility verifications.

This paper focuses on the mass flow rate of the PPS®5000 and on a tool set-up for in flight operations. More than a simple correlation tool from experimental test data, the entire dynamic simulation of the XFC (xenon flow control) based on EcosimPro® / Proosis® and ESPSS libraries (European Space Propulsion System Simulation) has been included in a black-box fashion in the tool, thus enabling the steady-state assessments as well as the dynamic transients.

The paper concludes with some examples of the use of the tool for the End-users for various inputs from in-flight data files or user-defined inputs.

## 1 Introduction

The Xenon feeding system of the Hall effect thruster PPS5000 is very similar to other Hall effect thruster except the mass flow rate that must be higher than for PPS1350 or SPT100 within a range between 4 and 28 mg/s. The mass flow rate delivered by the system is the main function of the XFC (Xenon Flow Controller). The mass flow rate depends on the environmental conditions (input XFC pressure, XFC temperature), on the commanded electrical current used to heat the thermo-throttle capillary tube included into the XFC, on the transients/history of previous uses and may depend also on several geometrical characteristics of the thermo-throttle capillary itself (diameters, length, rugosity of the internal thermo-throttle side) as well as on a physical property for the Reynolds number used to discriminate the transition between the turbulent flow regime and the laminar flow regime.

A simulation of the XFC requires a Multiphysics simulation tool because the heart of the XFC being the thermo-throttle capillary tube involve thermal, fluid flow dynamic (including turbulent and laminar flows) and electrical current. The existing tool EcosimPro® / Proosis® with the ESPSS library has been chosen as a main simulation tool. The next chapter presents that tool.

## 2 EcosimPro® / ESPSS

EcosimPro® is a Physical Simulation Modelling tool developed for ESA by Empresarios Agrupados Internacional (Spain) since 1989. Proosis® is dedicated release of EcosimPro oriented to turbo-fan is fully compatible with the libraries developed under EcosimPro.

EcosimPro was a precursor and now with its 33 years of careful growing, it belongs to the last generation of the common engineering tools after computer aided design (CAD) and integrated engineering analysis tools available on classical laptops. The kernel of EcosimPro is an expert solver of all the equations set in the different components of a system. Thanks to such expert solver, the tool allows to manipulate components like objects that can be independently further developed with more sophisticated equations. EcosimPro is based on a visual simulation tool for solving simple and complex physical processes that can be expressed in terms of equations (including ordinary differential equations and differential-algebraic equations) and discrete events.

Practically, 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, C++) but is very powerful to write any equations and differential equations for modelling continuous and discrete processes: the solver can manipulate the equations to extract the variables needed for the resolution of the system of equations, this is often called “acausal” or “symbolic manipulations”. 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 EcosimPro libraries written to model all aspects of a functional propulsion system. As a tool ESPSS is relying on 1D flow equations, thermodynamic relationships and real fluid properties, there is no need for fudge factors, therefore the results of the simulation could be considered as general as long as the flow is one-dimensional and homogeneous (either as mono-phase, or two-phase state or as a mixture). For some particular needs, the user can make new components by inheritance or from scratch.

### 3 Dynamic Simulation Model

The dynamic simulation of the XFC is implemented under EcosimPro tool [R 2] using the last release of the ESPSS library [R 3]. The full model will be disclosed in the next IAC conference [R 6].

All the components used to form the XFC model represent a large system of 12 000 equations which are to be solved with 100 boxes (i.e. coupled subsystems of algebraic equations) of type linear.

The model is designed for using it as black-box independently from EcosimPro environment called "DECK" (with input files) as well as in the EcosimPro environment for normal authorized user using it with input data (as usual from the experiment file for experimented EcosimPro User).

Hence, the model includes 5 specific components dedicated for this kind of multi-use:



The components "FilterG" are used in the model for the inputs of Valve position (0 closed or 1 open), input Pressure in Pa, Temperature XFC TRP in K, Temperature of thermal radiative environment source in K and Thermo-throttle current in A.

The component includes two possible inputs and one output: this allows to connect either input from a file when used as DECK (with a first order filter in order to smooth abrupt changes), or to connect directly input data without filtering when used in the EcosimPro environment. Of course, a general switch based on the flag "DECK\_CASE" allows the selection of the relevant case of inputs.



The flag "DECK\_CASE" is set by default for using the model as a DECK with input files specified into the ESPSS components based on "FilterG".



The output data from the several "FilterG" components are then directly connected as inputs of the simulation model with two links to each of the valves command, one link to the input pressure setting, two links to input temperature for the xenon and for the TRP (temperature reference point) of the XFC, one link to the Satellite Node for radiative heat thermal transfers and eventually one control link for setting the thermo-throttle electrical current.

The simulation involves many thermal interfaces, not only the fluid thermal transfer with the thermo-throttle capillary tube wall, but also the conduction and radiative heat transfer with the other parts of the system and satellite interface.

Most of the components used are coming from the library ESPSS. In addition, some new components have been designed by inheritance from existing ESPSS components for simplifying the design or for adding functionalities:



Two thermal conductors components have been improved in order to transfer proportionally the heat flux from a component of dimension 1 to a discretized component of dimension "n", those are the components "GLG" and "GRG" derived from ESPSS respectively "GL" and "GR". In addition, the component GRG takes into account the emissivity of the discretized component of dimension "n" for each node as a function of each node temperature.



Also the ESPSS component "CurrentConstant" has been improved to "CurrentConstantCmd" for enabling an independent command of the thermo-throttle electrical current into the capillary tube.



The "Lee" restrictions are using directly the "junction" component of ESPSS with an input in the area of the junction set by the equation  $A_o = 1 / (2600 * Lohm) \text{ m}^2$  where Lohm stand for Liquid ohm as defined by the Lee Company for its restrictions.

The main active components of the model are specific to the thermo-throttle. Those are:

Component "TubeT" is primarily derived from the ESPSS "Tube" which includes a 1-D discretization of the compressible fluid into "n" nodes. TubeT allows in addition, the input for changing the Reynolds Number set for the end of the laminar flow, and use the refined formulations of pressure losses for the flow in curved lines in turbulent and laminar conditions. Note: TubeT can also take into account the change of internal diameter due to the thermal expansion along every nodes of the discretization of the tube, but this feature was adding sometimes an increase in computation time without any noticeable relevant improvement in the results. Hence the variation of the internal diameter with the temperature has been eventually inhibited within this component.

Component "CylinderElecHeat" derived from the ESPSS "Cylinder" which includes a 1-D discretization of the metallic cylindrical envelope into "n" nodes, represents the wall of the capillary tube taking into account the electrical current from the electric power supply and transforms the electric power into thermal power (by joule effect) in heating each node of the discretized component.

Note: This heating power is further dissipated at the internal fluid side (thanks to Nusselt correlations) in the connected component "TubeT" and on the external side by radiative exchange in the connected component "GRG"..

### 3.1 Characteristic "mfr versus Itth". with the XFC Dynamic Simulation Model

A large set of steady state mass flow rate (mfr) test results for various samples and various pressure (1.77 bar to 2.83 bar), temperature (-40 to +110°C) and thermo-throttle current (Itth : 0 to 2.5 A) has been analyzed and eventually the test data mean value among several samples have been integrated in the simulation tool as look-up table.

For each integration step, the simulation tool output the mass flow rate simulated and the corresponding value from the look-up table with the inputs in terms of Pressure, Temperature and thermo-throttle current. Such feature allows to compute the differences between simulation results and mean test data for the whole simulation durations and for all the iso-pressure and iso-temperature cases considered.

The simulation is performed for a very long simulated duration (45 000 seconds) with the very slow increase of the thermo-throttle current (rate 0.2 A per hour): for such case, the answer from the model can be considered as quasi instantaneous without influence from the time constant while covering the whole characteristic versus the thermo-throttle current.

The plot of the simulated mass flow rate versus time is shown in Figure 1.

Because in the experiment of the model, the thermo-throttle current is proportional to the time, this plot is equivalent to the characteristic "mass flow rate versus thermo-throttle current", see [R 5]. The best fitting of the model data (within the tolerances range for internal diameter, external diameter, etc.) produces a very low residual standard deviation of 1.83% over the whole range of data. Taking into account the 3D input map of tests results in terms of pressure, temperature and thermo-throttle current, this can be considered as a remarkable achievement: all the simulation results (bold lines in Figure 1) are superposed or very near the mean test data (thin lines in Figure 1).

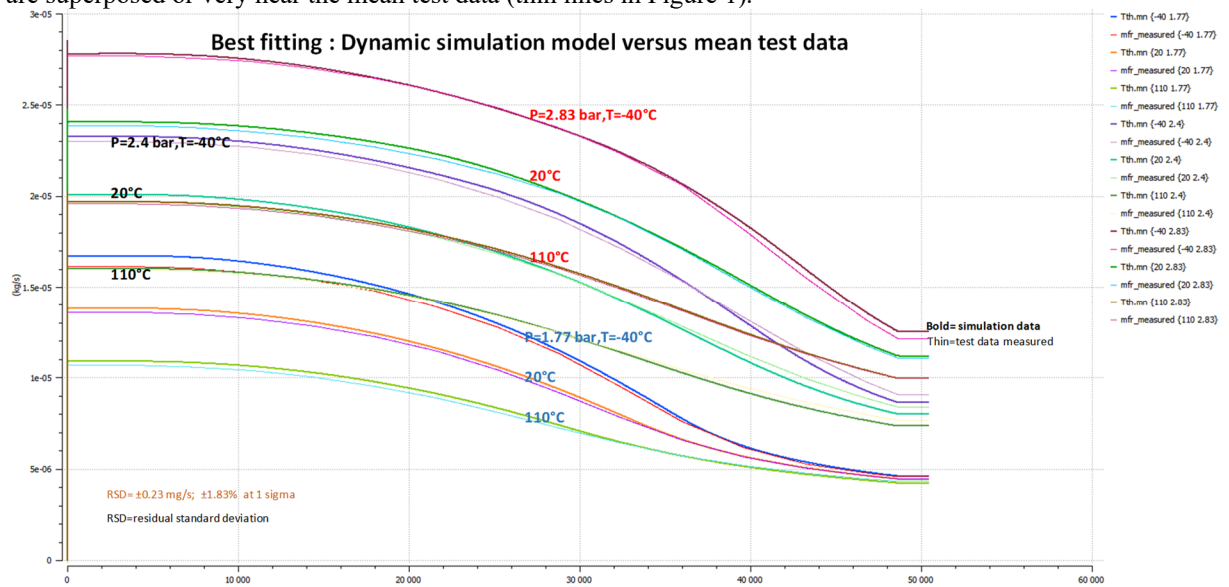


Figure 1: XFC model simulation results (bold lines) compared to the mean test data (thin lines)

### 3.2 Time response of “mfr versus Itth steps”. with the XFC Dynamic Simulation Model

A large set of mass flow rate and thruster discharge current (ID) results versus time for various pressure (1.8 bar to 2.4 bar) and thermo-throttle current steps (steps up or steps down of various amplitude between 0 and 2.5 A) has been analyzed. The behavior of the dynamic response measurements of the discharge current versus the thermo-throttle current steps shows a close analogy with a first order system. The Figure 2 shows that the measurements response (in non-dimensional form, dark-blue dots) can be closely compared to a first order system (pink dots) based on the same thermo-throttle current steps. The “counter time” in the horizontal axis represents the time from the beginning of the thermo-throttle current steps.

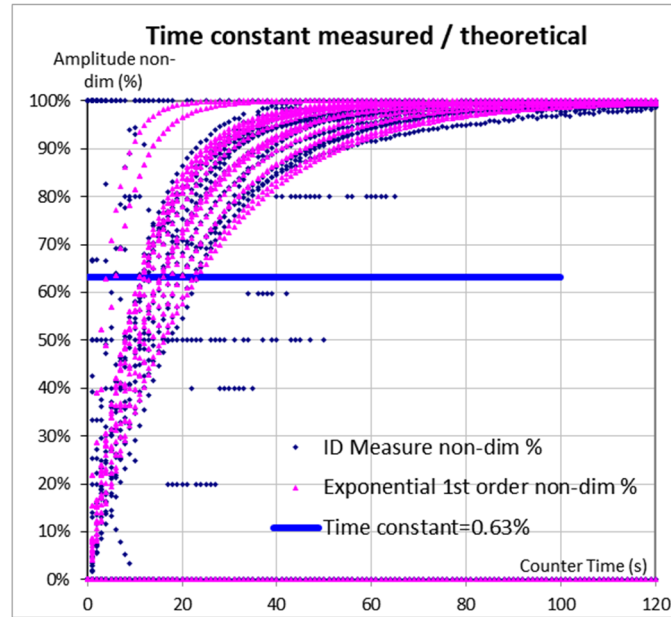


Figure 2: Non-dimensional time constant from ID measurement compared to a first order system

From the whole sequence of data measurement versus time, the following data have been selected: time, pressure and thermo-throttle current for being integrated in the simulation tool as look-up table. This set of data provides to the dynamic model: the pressure setting and the thermo-throttle current settings versus time.

The output of the dynamic model is shown Figure 3.

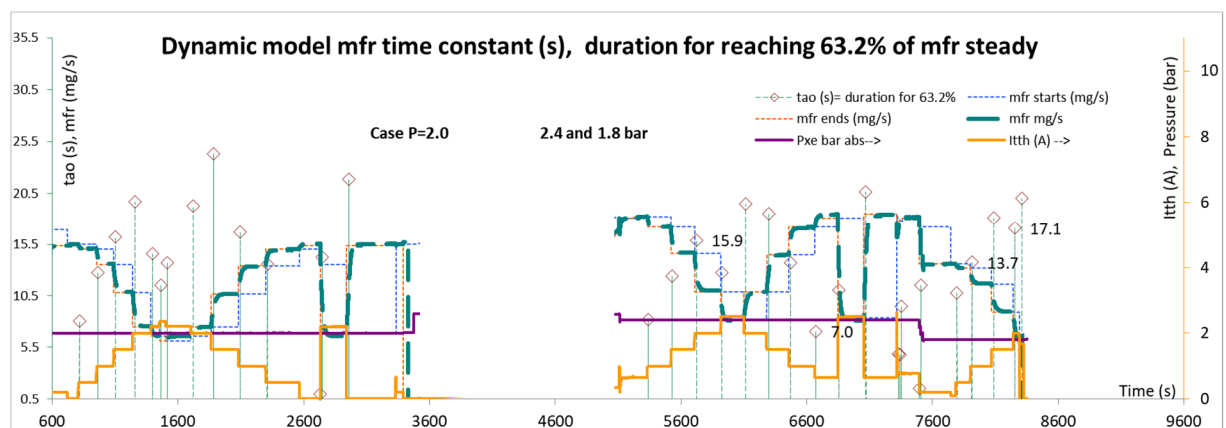


Figure 3: Dynamic response of mass flow rate for the real sequence (time, P, Itt) followed in tests

The comparison between the mass flow rate time constant computed by the dynamics model and the one measured (on the discharge current of the thruster) for all cases of steps in thermo-throttle current amplitude and direction (up or down) is excellent with respectively for the simulation: 7 to 24.4 s and 8.8 to 29.1 s for the measurements.

## 4 Dynamic Mfr Xfc Tool (EcosimPro Deck)

The previously described simulation model can be provided as a stand-alone black box tool with a GUI (Graphical user interface) made in an Excel sheet with a selection of inputs and outputs available for the end-user.

The tool is running on an Excel®. For using the tool as a stand-alone black box tool (totally outside the Ecosimpro environment), the end-user shall first install a free of charge specific Excel Add-in " EcosimPro tool bar " by running the installer "EAISetup\_EcosimPro.msi" located in DECK64Set folder delivered to the end-user. This action is needed only one time at all, and can be used for many other purposes that the Mfr Xfc Tool presented here.

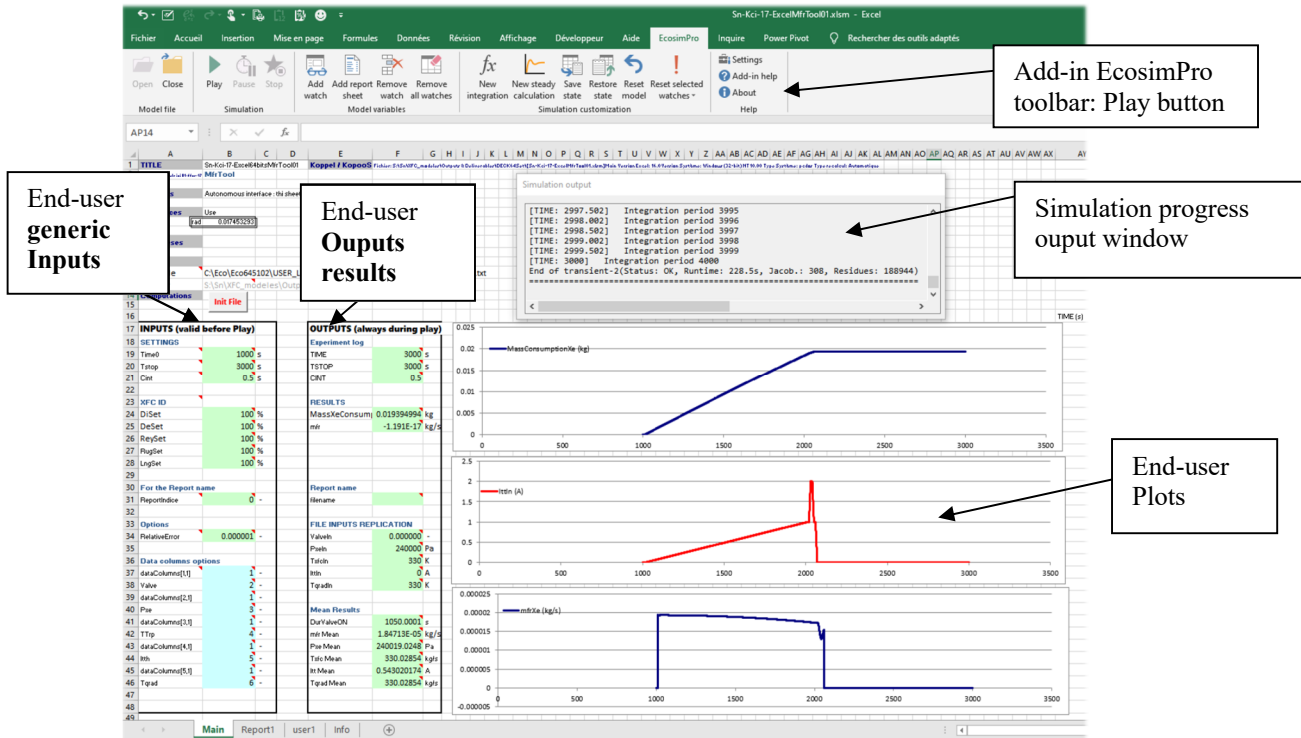


Figure 4: Mfr XFC Tool within the Excelsheet: general view

### 4.1 Input file for the Ecosimpro Deck Mfr Xfc Tool

The input data in terms of sequence and events (time, valves position, pressure, temperature, thermo-throttle current,...) shall be provided by the End-user within an input file.

An example of input file is shown in the Table 1 below. This file exists already directly in the DECK64Set folder (Note: to copy other file with the same name in the DECK64Set folder: this is to be done before opening the Excel sheet, or at least before the first use of the Play button of the EcosimPro tool bar).

Table 1: Example of input file needed for the Mfr Xfc Tool

| time(s) | Valve(0/1) | P(Pa)  | T(K) | Itth(A) | Tgrad(K) |
|---------|------------|--------|------|---------|----------|
| 1000    | 0          | 240000 | 330  | 0       | 330      |
| 1010    | 1          | 240000 | 330  | 0       | 330      |
| 2010    | 1          | 240000 | 330  | 1       | 330      |
| 2020    | 1          | 240000 | 330  | 1       | 330      |
| 2030    | 1          | 240000 | 330  | 2       | 330      |
| 2040    | 1          | 240000 | 330  | 2       | 330      |
| 2050    | 1          | 240000 | 330  | 1       | 330      |
| 2060    | 0          | 240000 | 330  | 1       | 330      |
| 2070    | 0          | 240000 | 330  | 0       | 330      |
| 2080    | 0          | 240000 | 330  | 0       | 330      |

In this input file, the first column contains the time (s), and 5 columns for the valve position V (0 or 1), the pressure P (Pa), the temperature T (K), the thermo-throttle current Itth (A) and for the temperature of the radiative source Tgrad (K).

#### 4.2 Features of the Ecosimpro Deck Mfr Xfc Tool

The screen copy Figure 4 shows the essential features of the two important parts dealing with the “End-user generic **Inputs**” and with the “End-user **Ouputs results**”.

#### 4.3 Generic input in Excel

As one can see in Table 2, the generic input data are set in the simplest way in the Excel sheet.

Those generic inputs deals with the duration of the simulation, some specific settings provided by the thruster manufacturer for minimizing the dispersions of each unit delivered (with values of 100% for the nominal values of geometric data), some traceability features for the output reports, and as options, the relative error to be considered for the computations and the organization of the input file (various combinations with a single common column for the time with 5 other columns for the input parameters, or as this is the case when the data come from in-flight telemetries, each parameter can have its own SCET (spacecraft elapsed time). Note: As a general rule, any input setting shall be set before the first action on the Play button of the EcosimPro tool bar in order to be taken into account.

Table 2: Generic input data of the Main sheet

| <b>INPUTS (valid before Play)</b> |          |   | Comments  |
|-----------------------------------|----------|---|---|
| <b>SETTINGS</b>                   |          |   |   |
| Time0                             | 1000     | s | Put here the start time of the simulation   |
| Tstop                             | 3000     | s | Idem for the end of simulation  |
| Cint                              | 0.5      | s | Idem for the Communication interval (this is not the integration step, it is just the printing interval of time)  |
| <b>XFC ID</b>                     |          |   | Settings specific to an XFC hardware: its ID  |
| DiSet                             | 100      | % | Internal diameter of thermo-throttle  |
| DeSet                             | 100      | % | External diameter   |
| ReySet                            | 100      | % | Reynolds set  |
| RugSet                            | 100      | % | Rugosity  |
| LngSet                            | 100      | % | length  |
| <b>For the Report name</b>        |          |   |   |
| ReportIndice                      | 0        | - | Put 0 if not report is wanted, else put 0.001 for example   |
| <b>Options</b>                    |          |   |   |
| RelativeError                     | 0.000001 | - | By default, the dynamic model run with 10E-6 error (increase to 1E-5 allow faster simulation, but with less accuracy or error risks. See important note below *). |
| <b>Data columns options</b>       |          |   |   |
| dataColumns[1,1]                  | 1        | - | Input file column number for the time of the valve  |
| Valve                             | 2        | - | Input file column number for the value valve position (0 or 1)  |
| dataColumns[2,1]                  | 1        | - | Input file column number for the time of the Pressure   |
| Pxe                               | 3        | - | Input file column number for Pressure (bar)   |
| dataColumns[3,1]                  | 1        | - | idem  |
| TTrp                              | 4        | - | Input file column number for T (K)  |
| dataColumns[4,1]                  | 1        | - | idem  |
| Itth                              | 5        | - | Input file column number for Itth (A)   |
| dataColumns[5,1]                  | 1        | - | idem  |
| Tgrad                             | 6        | - | Input file column number for Tgrad (K)  |

#### 4.1 Output data of the simulation

The second main part of the Excel sheet is dealing with the outputs of the simulation. In the Table 3 one can see the progress of the simulation with the time running, the instantaneous mass flow rate of xenon including transients as well as the total mass of xenon consumption since the starting of the simulation, the reports files generated, a very useful replication of the input file data and eventually the mean values for several parameters.

#### 4.2 Play to run the simulation

Once all the input data are correct, in order to run a simulation, the user shall click on "open" button in the EcosimPro tool bar. After a while, the user can still modify the input data in the Excel sheet. To run the simulation the end-user shall click on the "Play" button in the EcosimPro tool bar. The results are shown in the outputs window and the tool react automatically by updating the cells of the Excel sheet: as shown in

Table 3, at the end of the example, the xenon mass used is 19.39 g for the whole run.

Table 3: Output data of the Main sheet

| <b>OUTPUTS (always during play)</b> |             |      |
|-------------------------------------|-------------|------|
| <b>Experiment log</b>               |             |      |
| TIME                                | 3000        | s    |
| TSTOP                               | 3000        | s    |
| CINT                                | 0.5         | s    |
| <b>RESULTS</b>                      |             |      |
| MassXeConsumption                   | 0.019394994 | kg   |
| mfr                                 | -1.191E-17  | kg/s |
| <b>Report name</b>                  |             |      |
| filename                            |             |      |
| <b>FILE INPUTS REPLICATION</b>      |             |      |
| ValveIn                             | 0.000000    | -    |
| PxeIn                               | 240000      | Pa   |
| TxfcIn                              | 330         | K    |
| IttIn                               | 0           | A    |
| TgradIn                             | 330         | K    |
| <b>Mean Results</b>                 |             |      |
| DurValveON                          | 1050.0001   | s    |
| mfr Mean                            | 1.84713E-05 | kg/s |
| Pxe Mean                            | 240019.0248 | Pa   |
| Txfc Mean                           | 330.02854   | kg/s |
| Itt Mean                            | 0.543020174 | A    |
| Tgrad Mean                          | 330.02854   | kg/s |

Comments (here at the end of the run)

Shows the current time

Shows the time at end of simulation

Shows the current Communication interval

Shows the total mass consumption

Shows the mass flow rate in the thermo-throttle at current time

Shows the name of the report if any

Shows the replication of the input file data progress  
(filtered with a one order filter of time constant= 0.1s)

Shows mean data over the valve open duration

valve open duration during the run duration

Mean Mass flow rate

Mean Pressure

Mean Temperature

Mean Itth thermo-throttle current

Mean Tgrad temperature for radiative heat transfers



## 5 Other example: Smart-1 data in flight

For this example, the input data are organized in a different column shape than before.

Here each input parameter has its own SCET timestamp from the flight the SMART-1 Moon Probe using a single PPR®-1350 for the travel from Earth to Moon [R 4].

Hence there are 10 columns in the input file and the number of the columns is set in the Excel sheet accordingly: columns 1 and 2 for the timestamp of valve and for the valve value; columns 3 and 4 for pressure timestamp and pressure value, etc.

|    |                      |    |   |
|----|----------------------|----|---|
| 35 |                      |    |   |
| 36 | Data columns options |    |   |
| 37 | dataColumns[1,1]     | 1  | - |
| 38 | Valve                | 2  | - |
| 39 | dataColumns[2,1]     | 3  | - |
| 40 | Pwe                  | 4  | - |
| 41 | dataColumns[3,1]     | 5  | - |
| 42 | TTrp                 | 6  | - |
| 43 | dataColumns[4,1]     | 7  | - |
| 44 | lth                  | 8  | - |
| 45 | dataColumns[5,1]     | 9  | - |
| 46 | Tgrad                | 10 | - |
| 47 |                      |    |   |

of

The current XFC for the PPS®-5000 included in the Mfr Xfc Tool is not the one used for the PPR®-1350 during the SMART-1 flight, hence of course, the results in terms of mass flow rate are not relevant because largely different from the mass flow rate of SMART-1.

However, the values of the parameters recorded during the flight are fully compatible with the one required as input file by the Mfr Xfc Tool: by using this database in-flight it is shown the operational capability of the Mfr Xfc Tool developed.

The simulation starts at time= 44500 s (just before the first use of a PPS®-1350 in flight), and ends 48500 s (after the end of the first thrust pulse).

For this example, there are no specific XFC ID, so only default values at 100% are used.

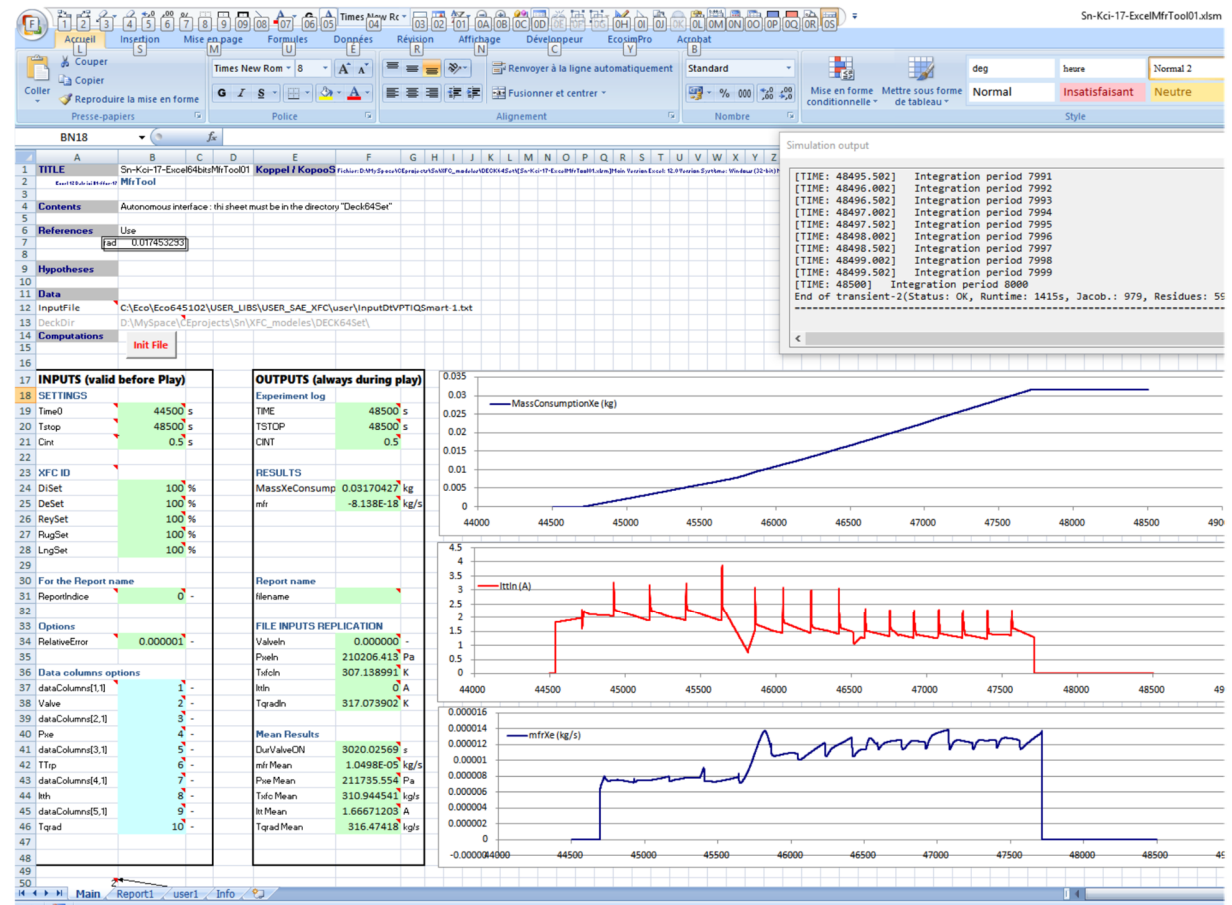


Figure 5 screen copy of the main sheet fed by the Smart-1 data in flight

The results are shown in the above screen copy: the xenon mass used is 31.70 g for the whole run (=cell F24). The shape of the thermo-throttle current input value (lthIn) used as input current for the tool is well reproduced in the plot Figure 5. The mass flow rate computed by the tool shown in Figure 5 is in line



with the expectations (except of course as already explained above for the scaling factor between PPS®-5000 and PPS®-1350).

## 6 Conclusions

A complete dynamic model of XFC (Xenon flow controller) has been designed with the software EcosimPro® and ESPSS (European Space Propulsion System Simulation) and with the help of some specific components designed by inheritance from existing components. The results of the simulations compared with steady state test results shows a very good fitting with a remarkable residual standard deviation of only 1.83%. The dynamic response of the simulation model has been compared to the measurements thanks to the time constant duration (by analogy to a first order system). Comparison for both time constant is excellent with respectively for the simulation: 7 to 24.4 s and 8.8 to 29.1 s for the measurements.

It is important to mention that the results of the EcosimPro® ESPSS have been obtained without any fudge factors and without any specific equations (the tool ESPSS is relying on 1D flow equations, thermodynamic relationships and real fluid properties, there is no need for fudge factors, therefore the results of the simulation can be considered as general as long as the flows are homogeneous one-phase or two-phase or mixtures with 1D discretization).

The paper shows that the complete dynamic simulation model of XFC has been successfully able to be run on Microsoft Excel® as a black box totally independent from the original simulation software.

The tool is a dynamic Mass flow rate tool called Mfr Xfc Tool set-up with the Ecosimpro Deck feature. This tool can be used by End-users for preparing their own mission analysis or directly from flight data for health checks or for improving book-keeping forecasts.

## 7 References

- [R 1] Olivier Duchemin et al., “Qualification Status of the PPS®5000 Hall Thruster Unit” IEPC-2019-906, 36th International Electric Propulsion Conference University of Vienna, Austria, September 15-20, 2019
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- [R 3] ESPSS EcosimPro Libraries User's Manual ESPSS Version: 3.2.4 Date: 06-01-2018
- [R 4] Christophe R. Koppel and Denis Estublier, IEPC-2005- 119 “The SMART-1 Hall Effect Thruster Around the Moon:In Flight Experience,” 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005.
- [R 5] Olivier Duchemin et al., “Extended Qualification Life Test of The PPS®5000 Hall Thruster Unit,” Space Propulsion 2022 Estoril, Portugal | 09 – 13 May 2022
- [R 6] Christophe R. Koppel et al., IAC-22-C4.5.10 “Dynamic Mass Flow Rate Model for PPS®5000 Hall Thruster Unit,” 73<sup>rd</sup> International Astronautical Congress (IAC), Paris, France, 18-22 September 2022 (to be published).