SPACE PROPULSION 2022 ESTORIL, PORTUGAL | 09 – 13 MAY 2022

A VALIDATION OF A HIGH-PRESSURE XENON COLD GAS THRUSTER SIMULATION UNDER ECOSIMPRO® ESPSS

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KEYWORDS: Cold gas thruster, xenon, high pressure, Simulation, EcosimPro®, ESPSS

ABSTRACT:

The paper presents a simulation model to forecast the performance of a High-Pressure Cold Gas Thruster used as auxiliary thrusters on All Electric satellite platforms (as already mentioned in the patent [R 1]) using Xenon gas 2-phase liquid vapor for a large range of input pressure at constant input temperature.
The important question to be solved is the validation of the simulation model. Thanks to reference Maxar-Moog [R 4] exhibiting several experimental data like Isp, Thrust force and mass flow rate versus input pressure (at constant temperature), it becomes quite easy to set-up the cold gas thruster model for the conditions set in that reference, and the superposition of the simulations results with the reference data enable the answer regarding the validation.
The cold gas thruster model relies on the existing EcosimPro® simulation tool [R 2] and ESPSS (European Space Propulsion System Simulation) [R 3] which manage real gas and real liquids as well as mixtures 2-phase flows (liquid + vapor).
In order to be as simple as possible the model incudes a xenon volume, a valve directly connected to the upstream volume, a nozzle directly connected to the valve downstream and an exhaust section with supersonic junction connected to the vacuum. Moreover, in order to avoid any perturbation due to the thermal exchanges between walls and xenon gas flow inside, the components are simply volumes without any walls but with a thermal port connected to a regulation in temperature (for the xenon volume) and to a perfect insulation (for the nozzle). The valve and supersonic junction have no walls and no thermal port so the simulated flow from the xenon volume to the exhaust section of the thruster nozzle is purely adiabatic.
The simulation is performed with the tank pressure varying from 18.6 MPa down to 0.25 MPa (a blow-down mode from a large tank volume). This enables to perform the full picture of main performances results in terms of Isp, Thrust force (along with mass flow rate) for the large input pressure range at once.
The validation of EcosimPro® ESPSS for a High-Pressure Xenon cold gas thruster is very successful. Over the whole range of pressure 18.6 MPa down to 0.25 MPa, the EcosimPro® ESPSS results match very well with the experimental data published in [R 4].
One shall mention that for the Isp, the results from EcosimPro® ESPSS seems much closer to the experimental data than the simulation model shown in [R 4]. This successful result has been obtained thanks to the availability of the valuable experimental results disclosed.
One shall recall 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).

1. WHY THE INTEREST IN XENON COLD GAS THRUSTER

It is well known that cold gas thrusters based on xenon gas provides a very “poor” performance in terms of Isp. However, the high density of the xenon gas under pressure can be used to compensate the drawback in performance at system level with very low mass of tanks compared to higher Isp propellants but at quite low storage density. This feature makes the xenon gas quite optimum for some small sat with reduced needs in terms of delta-V. But the main interest in xenon cold gas thrusters becomes more obvious at the era of the all-electric satellites. As quoted in the 1996 patent [R 1] “*In this way, only one type of thruster is required for putting the satellite into its target orbit. However, it is not impossible to include auxiliary thrusters of other types, such as cold gas thrusters or resistojets, and making use of the same gas as the high specific impulse thrusters, e.g. xenon, thereby making it possible during short*

instants to obtain greater thrust levels, while avoiding the above-mentioned drawbacks of chemical thrust. Such auxiliary thrusters may be used in an initial stage..." hence, the all-electric satellites may rely for short periods of time on auxiliary thrusters using the same propellant as the main propulsion system (even when using the xenon gas, this is the concept of unified propulsion system known for minimizing the margins in propellant contrary to non-unified systems) for enabling greater thrust levels and with a greater availability than the main electric thrusters.
This principle of unified propulsion system with xenon has been adopted on-board the ESA program SGEO (Small GEO satellite) in 2008 and launched early 2017.

2. HIGH/LOW PRESSURE XENON COLD GAS THRUSTER

Within the principle of unified xenon propulsion system, the feeding in xenon of the cold gas thruster can be provided directly from the high-pressure tank (with non-regulated input pressure) or from the low-pressure output from the pressure regulator which is needed in any case for the main Electric thrusters. In such last case, the advantage is of course to be able to provide a regulated thrust and to use in the system only low-pressure valves (latching or not). However, in this case, the mass flow rates for the cold gas thrusters can be much higher than the one needed for the main EP (electric propulsion) thrusters: this induces additional constraints to the pressure regulator coming from larger mass flow rate with larger thermo-dynamic effects to be mastered with thermal control and additional heaters. While when the xenon come directly from the high-pressure tank, such disadvantage disappears, at the price to use in the system qualified high-pressure valves (latching or not) and to provide non-regulated thrust. Because, as explained before, the cold gas thrusters are only used for covering non-nominal cases (to perform an eventual detumbling at the S/C (spacecraft) separation from the launcher, or to perform suited torques during the Solar array deployment, etc.), the importance of relying on a regulated thrust cold gas thruster is les obvious if a simulation model can be provided for enabling an accurate forecast of the thrust and mass flow rate to be managed by the AOCS (attitude and orbit control system) of the S/C. With high-pressure xenon cold gas thrusters, it is thus mandatory to rely on an accurate simulation model validated for a wide range of pressure and temperatures. Such validation of simulation model is for now on the important subject of the following chapters.

3. REAL 2-PHASE FLOW ANALYSIS

The xenon gas stored at high pressure will see, during the detent to vacuum, states characterised by two phase flows. The thermodynamic of the detent is far from the theoretical detents found in classical books. Hence numerical simulations are mandatory for managing properly those real cases.
In addition, the generally considered adiabatic flow (without heat transfers between the hardware and the fluid) can be enhanced by a real heat transfer thanks to the numerical simulations.

4. SIMPLE SIMULATION MODEL

A simple model has been set up in order to forecast the performance of a cold gas thruster using Xenon gas including 2-phase liquid vapor for a large range of input pressure at constant input temperature.
In order to be as simple as possible the model incudes a xenon upstream volume, a valve directly connected to that volume, a nozzle directly connected to the valve downstream and an exhaust section with supersonic junction connected to the vacuum, see Figure 1.

- Moreover, in order to avoid any perturbation due to the thermal exchanges between walls and xenon gas flow inside, the components are simply volumes without any walls but with a thermal port connected to a regulation in temperature (for the xenon volume) and to a perfect insulation (for the nozzle). The valve and supersonic junction have no walls and no thermal port so the simulated flow from the xenon volume to the exhaust section of the thruster nozzle is purely adiabatic for this simple model.
- The model set-up relies on EcosimPro® simulation tool [R 2] and ESPSS (European Space Propulsion System Simulation) [R 3] which manage real gas and real liquids as well as mixtures 2-phase flows (liquid + vapor).
- In the following model, the xenon volume is named "Vol1". Its temperature regulation is performed by a thermal boundary node called "BN" with fixed temperature set by the analogue input component "Ttank". To minimize the temperature variation, the volume of "Vol1" shall be very large (100 m3).
- The Cold gas thruster is simulated by a high pressure ON/OFF solenoid valve called "KY1" and the nozzle is simulated by a tube volume with a simple diverging cone (half angle of 15°) called "Nozzle" (note that even if its icon is shown as a rectangle, the discretization 1D of the tube allows to set a diverging profile). The exit of the CGT (cold gas thruster) is made of a supersonic Junction called "sJunction" connected to the Ambient.

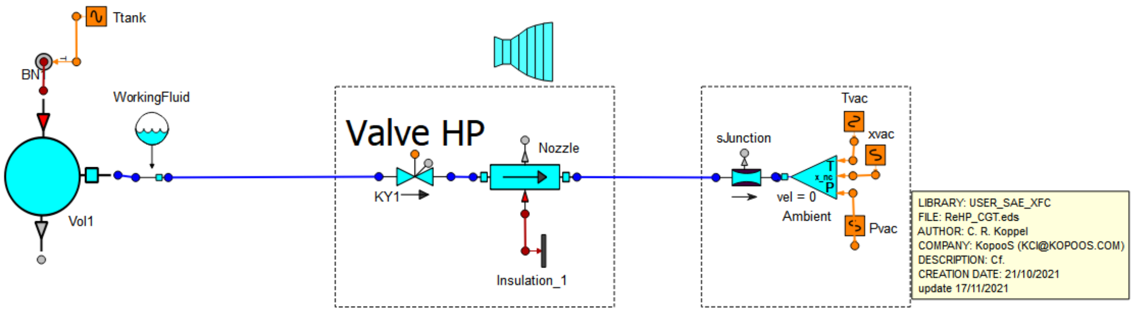

Figure 1 EcosimPro® model of a cold gas thruster using components from the ESPSS library

The purpose of this analysis being to validate the results from EcosimPro® ESPSS simulation, this model is checked with respect to the reference Maxar-Moog [R 4].
Hence, the EcosimPro® experiment takes into account the following input data:

- The xenon tank temperature is set to 21°C (294 K) and the initial pressure is set at 2700 psia (18.6 MPa) as in [R 4].
- The xenon consumption will make the pressure decreasing during the experiment for the whole pressure range down to 0.25 MPa.
- The nozzle expansion ratio (epsilon = exit area/ throat area) is taken equal to 100 as in [R 4].
- Hypothesis for data not disclosed in Maxar-Moog [R 3]
  - The nozzle profile is a half cone 15° , the boundary layer thickness considered by EcosimPro® ESPSS being zero, the real hardware profile of the nozzle should take into account the real boundary layer thickness for getting similar results as the one obtained from EcosimPro® ESPSS
  - The absolute rugosity of the supersonic nozzle has been taken at 10 µm.
  - The valve seat area is equal to the Nozzle throat area.
  - However, the diameter of the valve seat being not disclosed in [R 4], it is determined such that with the previous assumptions and <u>only for one single experimental point</u>, the value of the thrust coincides with the one of the reference [R 4]
    - the chosen point is at highest pressure 2700 psia (18.6 MPa) and for 21°C,
    - the experimental thrust result is 2.85 N.

    This is done with a simple trim on the diameter which gives 0.286 mm.
  - The heat from the solenoid valve has been neglected in the model. The whole flow including the Nozzle is working in adiabatic conditions.
  - The conductive and radiative heat transfers from tank, tubings, experimental baseplate and vacuum environment toward the nozzle have been intentionally neglected because not disclosed in [R 4], as neither the duration to reach the steady-state.

EcosimPro® ESPSS components particular settings:

- The number of nodes along the 1D Nozzle axis has been taken to 100, a higher number of nodes does not produce any significant change in the results while a much lower number of nodes (<20) makes the changes more significant.
- For simulating correctly, the critical conditions in the valve, the option “Gcr_ideal” is set to TRUE (the critical flow is computed in ESPSS using an isentropic evolution up to Mach unity in the Mollier diagram of the real gas).
- For getting a supersonic flow from the exit of the Nozzle toward the Ambient, the option “Choked_option” of the exit Junction is set to FALSE (the mass flow rate is not choked by this component as in the real world). Its “Gcr_ideal” option is also set to FALSE because it has no effect on the Isp and thrust values.
- The “Ambient” outside pressure is set to 0.000007 MPa (7 Pa) instead of pure vacuum (making simulation faster without any effect on the results).
- The thrust F and specific impulse Isp equations have been added to the model: because the tool compute mass flow rates $\dot{m}$ in kg/s and velocities v in m/s, the thrust equation in N is (with the pressures P in Pa and exit area A_{exit} in m²):

$$F = \dot{m}.v_{Nozzle\ exit} + (P_{exit} - P_{Ambient}).A_{exit}$$

- The *Isp* equation in s is given by :

$$Isp = \frac{F}{9.80665\,\dot{m}}$$

5. SIMULATIONS RESULTS

On Figure 2the following figures, the results of the EcosimPro® ESPSS simulation are superposed on the original plots from Maxar-Moog [R 4] which includes the Maxar-Moog model prediction curve and more important the experimental data.

5.1. ISP RESULTS

On Figure 2,, the comparison between EcosimPro® ESPSS and Maxar-Moog model experimental data is excellent:

- The Isp predicted by EcosimPro® ESPSS (green curve) fits well with the experimental data of Maxar-Moog. This is especially highlighted for all the range of input pressures, in particular for the red crosses experimental data of “Xe SN 0003 “.

- Note 1: It is important to recall that this result has been obtained without any fudge factors (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 could be considered as general as long as the flows are homogeneous, one-phase or two-phase or mixtures within a 1D discretization).

- Note 2: the Isp predicted by EcosimPro® ESPSS is a very general result as it does not depend on the thrust at first order.

- The shapes provided by the two models present the same step around the critical point of the Xenon.

- Note that the Maxar-Moog model prediction (blue curve) is good but quite pessimistic for medium and low input pressure wrt experimental data red crosses of “Xe SN 0003“.

- Also the Maxar-Moog model prediction seems flat for medium and low input pressure, while a slope up occurs for the EcosimPro® ESPSS model which is confirmed by the test results red crosses of “Xe SN 0003 “.

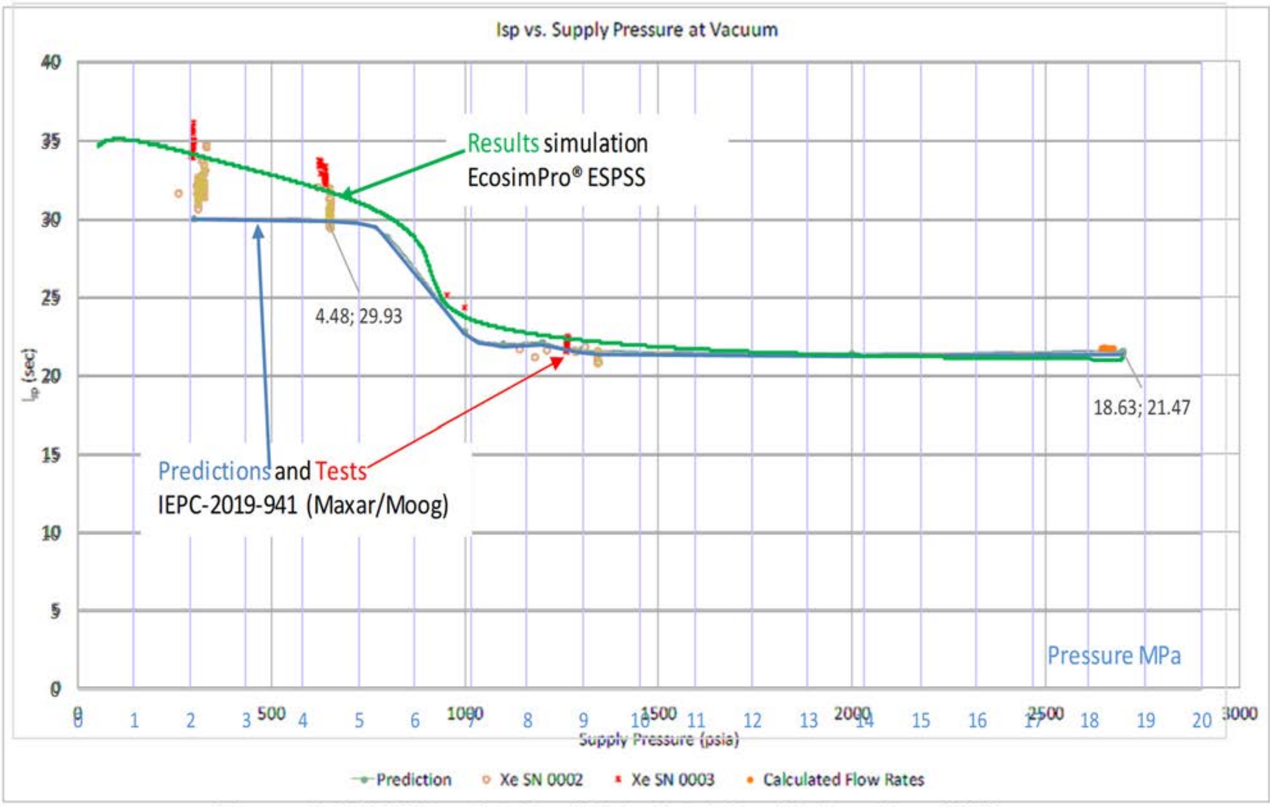

Figure 6. XCGT Predicted and Calculated Specific Impulse with Xenon Used by permission of Moog Inc.

Figure 2 Isp comparison EcosimPro® ESPSS wrt Maxar-Moog experimental results

5.2. THRUST AND MASS FLOW RATE RESULTS

Regarding the thrust, referring to Figure 3, the EcosimPro® ESPSS thrust results (with seat area trimmed such that the thrust is 2.85 N for the single point 18.6 MPa and input temperature 294 K) the two models are quite similar, with a better fit for the EcosimPro® ESPSS model, of course for the point at 18.6 MPa (because the throat diameter has been trimmed for producing the same thrust as the experiment for that point) but also for a majority of the other experimental results.

The mass flow rate analysis is a quite a redundant analysis, but anyway, once more, according to Figure 4, the two models are similar, with a better fit for the EcosimPro® ESPSS model especially for the high-pressure points (because the mass flow rate follows the thrust value, the Isp being a very generic value).

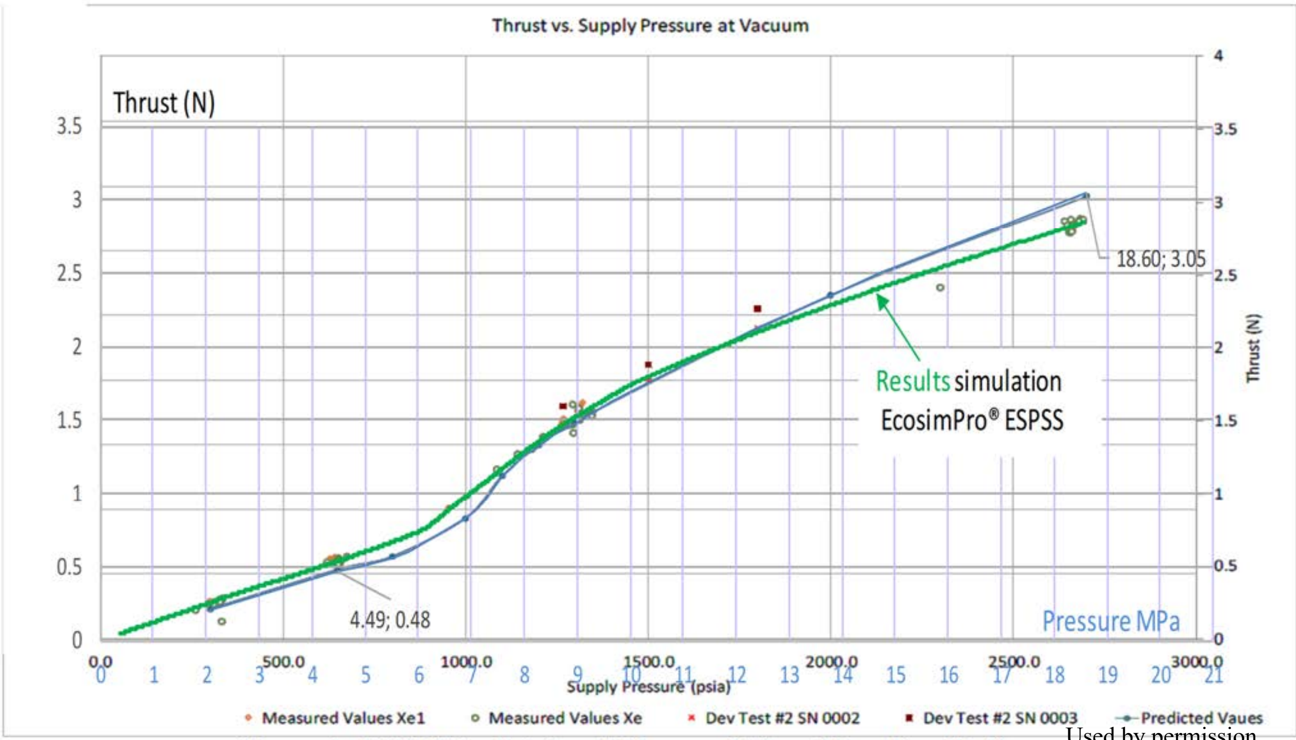

Figure 4. XCGT Predicted and Measured Thrust Results with Xenon Used by permission of Moog Inc.

Figure 3 Thrust comparison EcosimPro® ESPSS wrt Maxar-Moog model prediction and experimental results

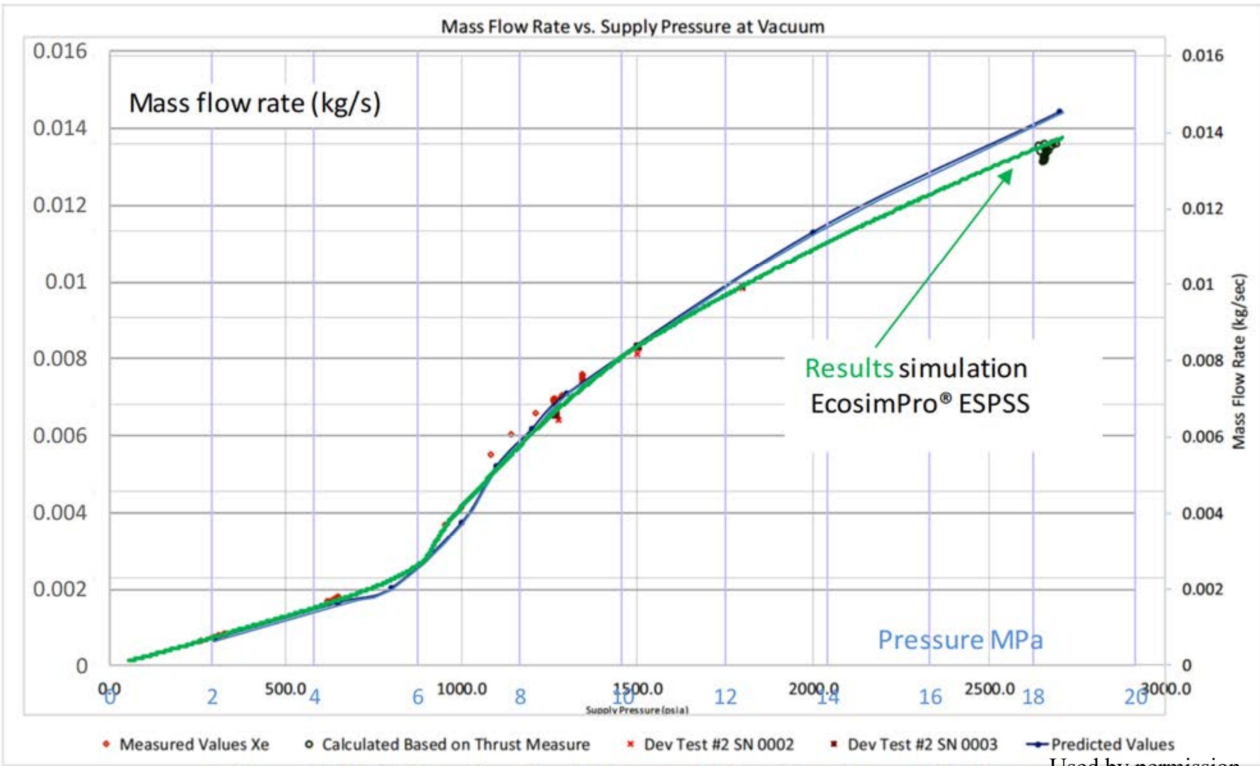

Figure 5. XCGT Predicted and Measured Mass Flow Rates with Xenon Used by permission of Moog Inc.

Figure 4 Mass flow rate comparison EcosimPro® ESPSS wrt Maxar-Moog model prediction and experimental results

6. ADDITIONAL THERMODYNAMIC RESULTS

The EcosimPro® ESPSS simulation provides many useful results other than the fundamental results in term of Isp and Thrust. Of course, temperature and pressure of the mixture along the nozzle and other components, but also enthalpy versus entropy or void volume and quality.

Those state functions are now computed at each port connection thanks to the additional variables declared in the “fluid” port:

```
REAL s              UNITS u_J_kgK "entropy at port"
REAL h_s = 1e5 UNITS u_J_kg "Static enthalpy"…
```

and thanks to the following equations added in the continuous section of “fluid” port

```
h_s=h-0.5*v*v
s = FL_prop_vs_ph (burnerGasesOption, dummy, fluid, P, h_s, fprop_entropy, T, ier)
```

where the generic existing function **FL_prop_vs_ph** provides the entropy value corresponding to the pressure P and to static enthalpy h_s for the given fluid.

The static enthalpy h_s is coming from the total enthalpy h (variable already included in the port) minus the specific kinetic energy 0.5*v*v coming from the velocity (variable already included in the port).

6.1. ENTHALPY (H) VERSUS ENTROPY (S) INTO A MOLLIER DIAGRAM

For each input pressure, the tool EcosimPro® ESPSS produces the evolution of the static enthalpy versus entropy along the thermodynamic cycle from the tank to the exit section of the cold gas thruster. The results are shown on the following Mollier diagram with the same initial temperature 294 K (21°C) and for several initial pressures between 18.6 and 1 MPa, including a pressure near critical point 6.63 MPa.

It is clear that such visualization of the xenon detent is not very common because of the particularities of the xenon gas and the starting input temperature so near the critical point. Most of the detent occurs in the 2-phase region (liquid + vapor) under the saturation line.

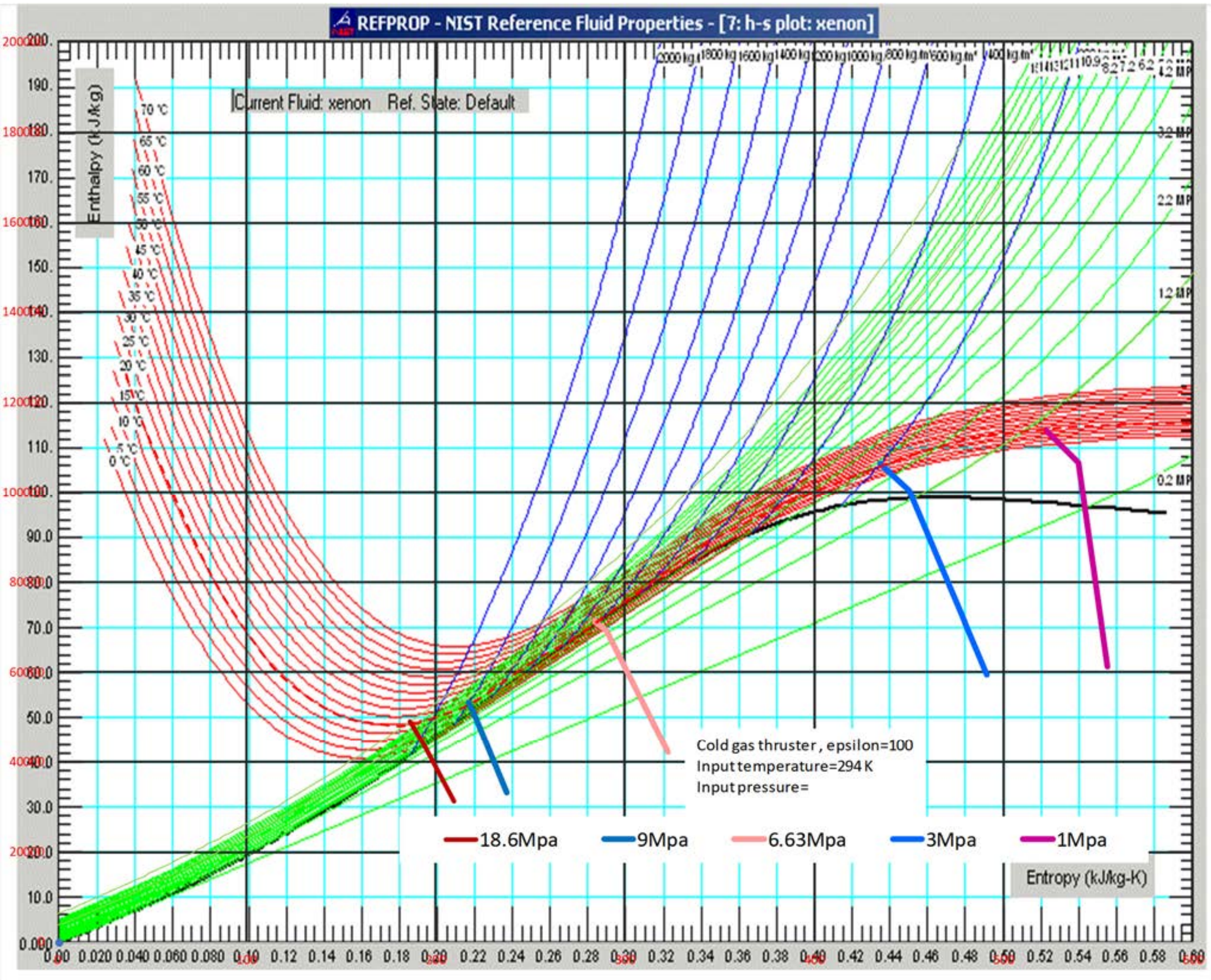

Figure 5 Detent results by EcosimPro® ESPSS for several input pressure (ε = 100) on the Xenon Mollier H S

6.2. VOID VOLUME AND QUALITY

The 2-phase flow in the nozzle is better described by the Void volume or the quality (mass fraction). The void volume called "alpha" ,

$$\alpha = void\ fraction\ per\ volume$$
$$\alpha = V_{vap}/(V_{vap} + V_{liq})$$

which is lower than 1 when liquefaction occurs.

The dual quantity is the quality called x

$$x = mass\ fraction$$
$$x = m_{vap}/(m_{vap} + m_{liq})$$

Note: $\alpha = x\frac{\rho_{mixture}}{\rho_{vap}}$

Those two quantities are plotted for several nodes in the nozzle versus time (i.e. for decreasing pressure) in Figure 6, Figure 7.
The void volume is very near unity because the volume of liquid is small, but of course when considering the mass fraction i.e. the quality x it is still significantly lower than the unity for the whole run, but increasing with the time, so when pressure decreases.
The increase of the quality versus the time (or versus decreasing pressure) explains that the Isp increases.

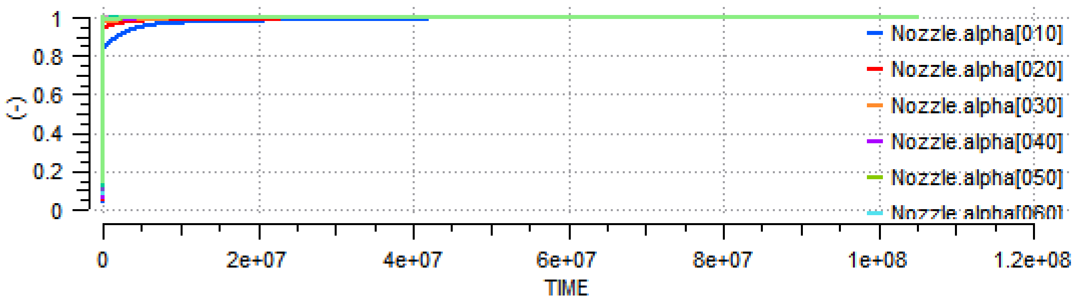

Figure 6 Void volume alpha along the nozzle versus the time

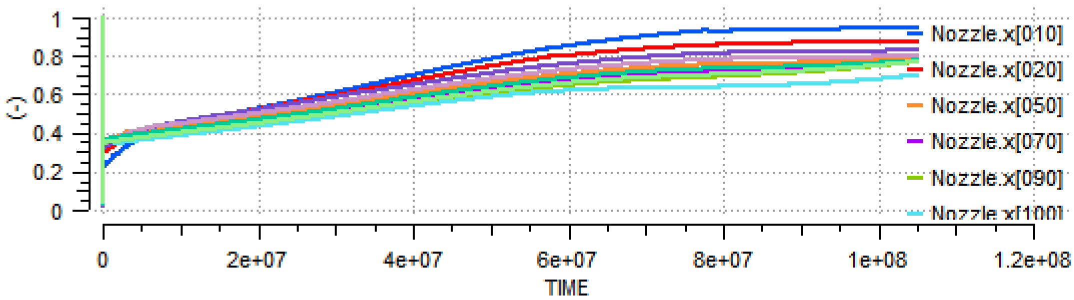

Figure 7 Mass fraction x quality along the nozzle versus the time

6.3. TRACEABILITY OF THE MODEL

For reference, the plots of the results of the simulation up to 105E6 seconds are shown below for traceability.

The first top left plot show that the tank Vol1 pressure is well decreasing from the maximum pressure, but its temperature varies during the run by less than 0.1 °C as expected.

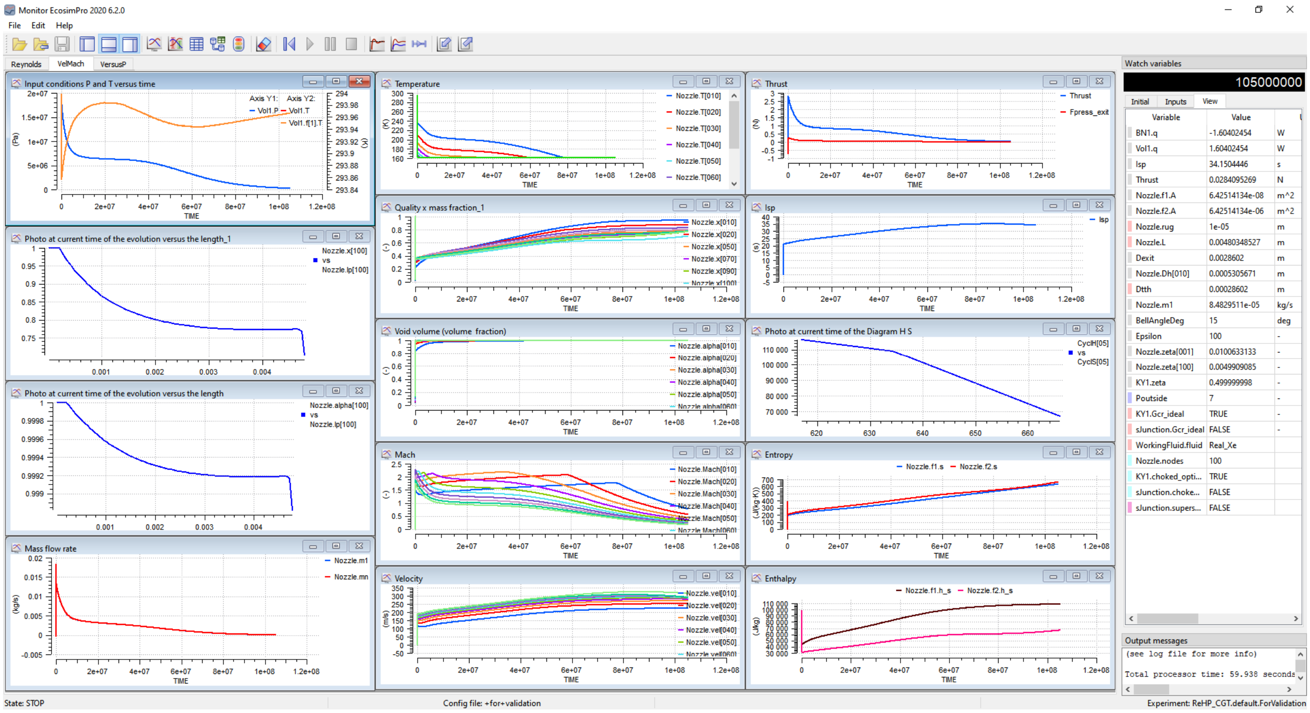

Figure 8 Simulation results Mach versus time, photos and H S cycle at time of simulation's end, etc

7. CONCLUSION

The validation of EcosimPro® ESPSS for a high-pressure Xenon cold gas thruster is very successful. Over the whole range of pressure 18.6 MPa down to 0.25 MPa, the EcosimPro® ESPSS results match very well with the experimental data published by Maxar-Moog [R 4].

One shall mention that for the Isp, the results from EcosimPro® ESPSS seems much closer to the experimental data than the Maxar-Moog simulation model itself which is already very good.

This successful result has been obtained thanks to the availability of the Maxar-Moog paper [R 4] and the valuable experimental results disclosed.

One shall recall 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 model used for the validation, as presented above, is very simple, with a minimum number of components and without any perturbation coming from thermal heat transfers, but of course with EcosimPro® ESPSS, refined model with tank, tubes (including walls), pressure regulator if any, upstream isolation valve and with conductive and radiative thermal transfers to thermal nodes (as in the real experiment) can be set-up (once data are available) to make refined simulations including dynamic transient analysis of the test set-up (important for the response time and thermal transients stabilization up to the steady state).

ACKNOWLEDGMENTS

The authors thanks Ian Johnson et al. from Maxar-Moog for their publication in the last IEPC conference in Vienna, 2019 [R 4], and for their permission to use their figures 4 to 6.

8. REFERENCES

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[R 3] "ESPSS 3.4 Nov. 2020

[R 4] Ian Johnson et al., Kevin Neff et al., "Xenon Cold Gas Thruster (XCGT)," IEPC-2019-941 Presented at the 36th International Electric Propulsion Conference, Vienna, Austria September 15-20, 2019