Performance Assessment of the ESM Ullage Pressure Control Assembly

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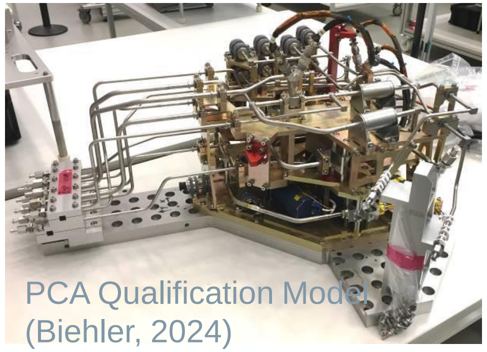
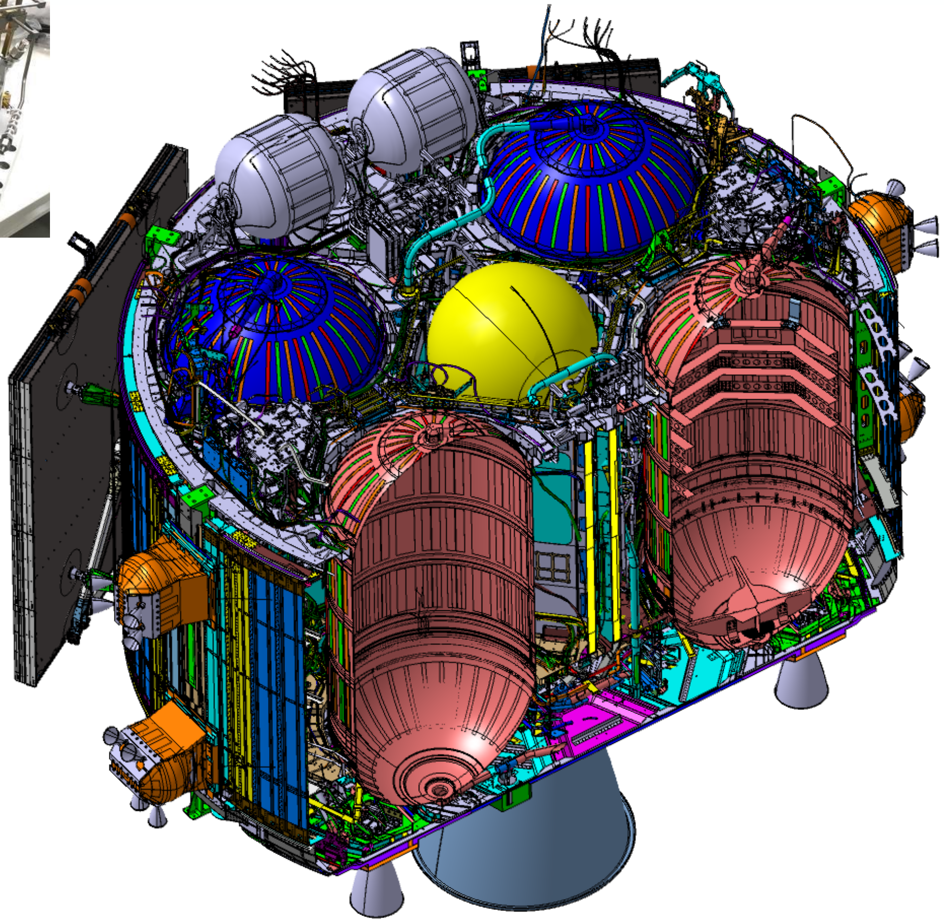
Aim of the Work

- The European Service Module (ESM) implements a bi-propellant propulsion system
- The propellant tank pressure is regulated by the pressure control assembly (PCA)
- There are two PCAs, one for each of the MON and the MMH commodities.
- Each PCA comprises two redundant branches
- Each branch integrates one bi-stable valve and two mono-stable valves in series with a flow control orifice.
- The flow dynamics throughout the PCA are very rapid and the resulting interactions between the valves need to be managed to limit the loads.
- A pneumatic model of the PCA was developed and validated against experimental results.
- The model was then used to assess the results observed during the acceptance tests of the flight hardware.



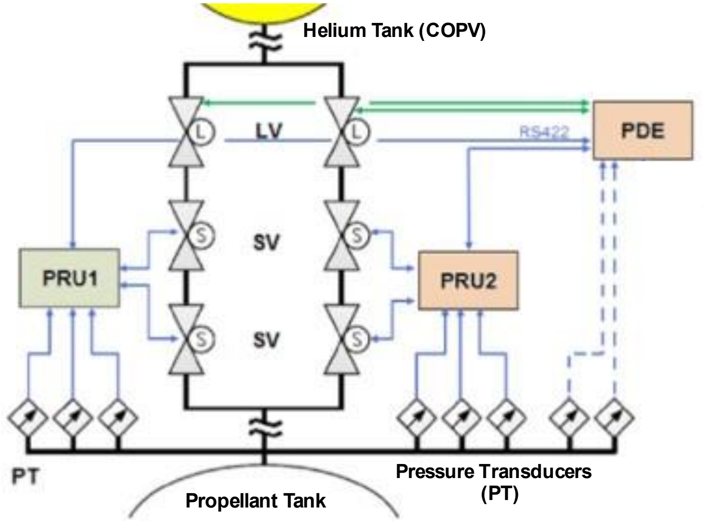
PCA Qualification Model (Biehler, 2024)

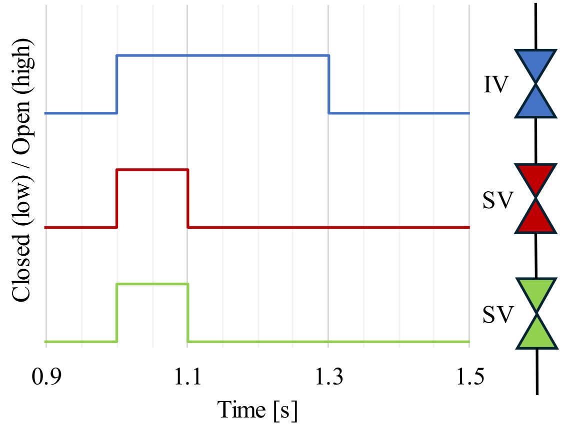


Overview of the ESM Propulsion Subsystem (J. H. Meiss, 2024)

Introduction

- The PCA of the ESM features a bang-bang control.
- The mono-stable solenoid valves (SV) are commanded open or closed simultaneously.
- The ullage pressure does not exceed the regulation bandwidth of 0.5 bar.
- The ullage remains at blanket pressure till the PCA is activated to raise the ullage pressure to a set point around 17 bar
- A dedicated sequence (aka flush-prime) was conceived to minimize the loads across the opening valves from the severe pressure inrush.
- The flush-prime sequence was executed for the first time during the acceptance tests of ESM-3 at Airbus DS in Bremen.
- The sequence led to unexpected differential pressure across the IVs, which increased over time following IV closure.
- Moreover, the pressures in the volumes between the valves were observed to match during the instants following the sequence, thus indicating that the upstream SV may have closed with delay with respect to the downstream SV. This was observed in two out of the four branches tested.
- A pneumatic model of the PCA was developed to investigate these unexpected results.

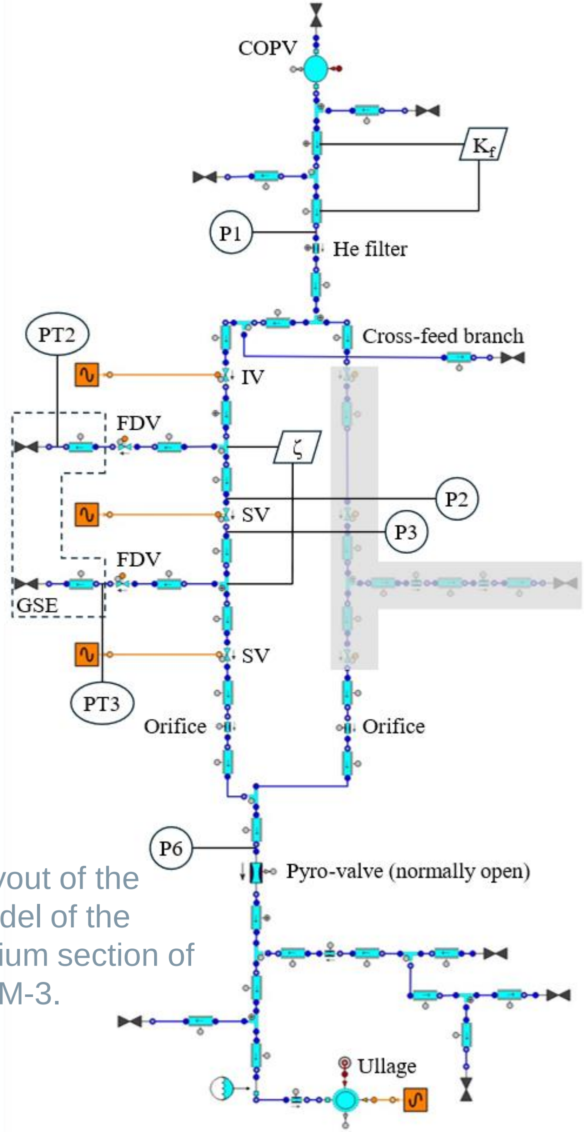




Flush-prime sequence.

Model Anchoring

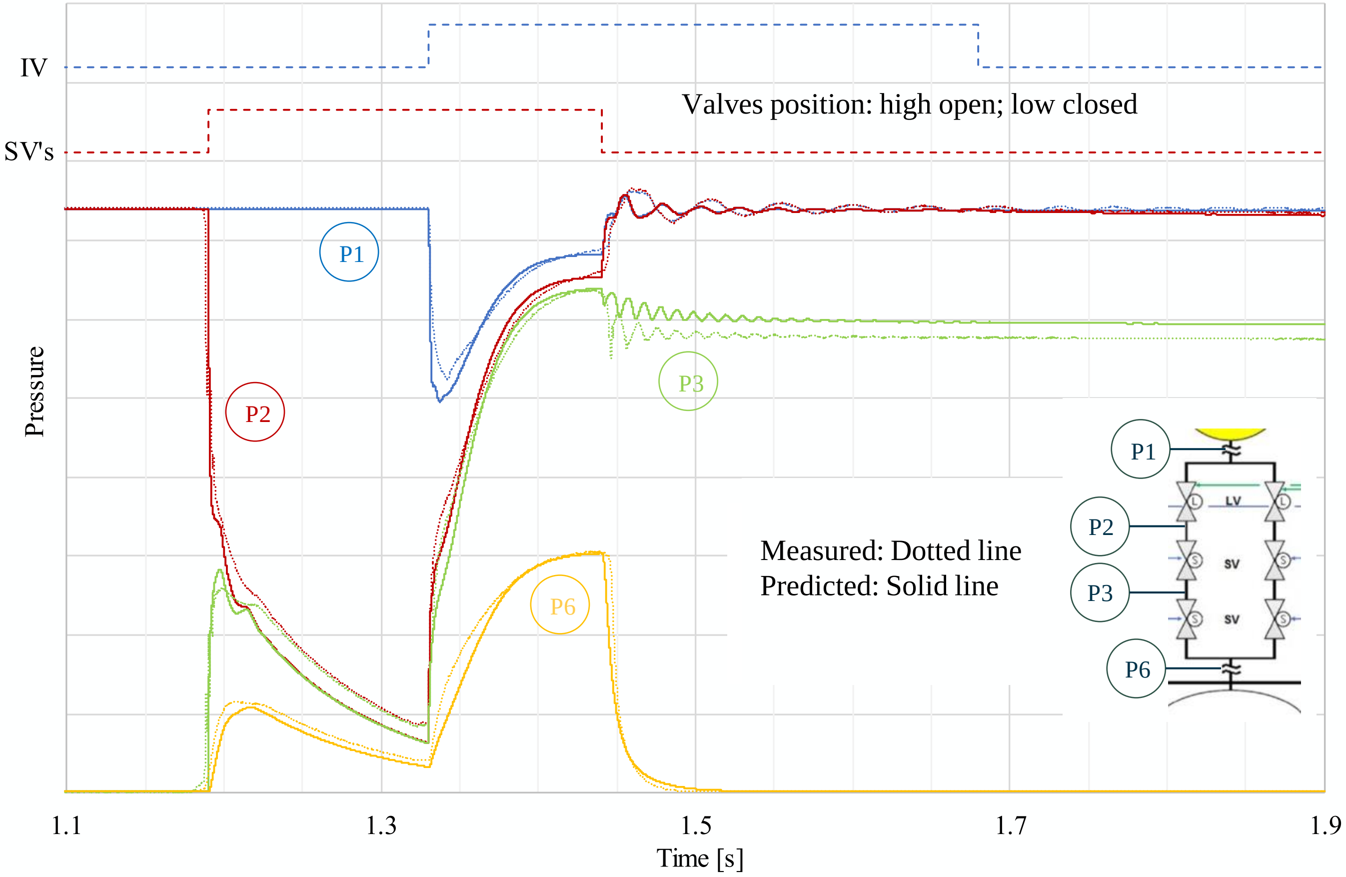
- The pneumatic model of the PCA was developed in EcosimPro with the European Space Propulsion System Simulation (ESPSS) toolkit.
- The actual geometry of the pipes was considered (from the ESM CAD file).
- The equipment in the gaseous section of the ESM is modelled by standard components from ESPSS as follows:
    - Helium filter: Installed in the PCA inlet, is modelled as an orifice and the pressure drop is correlated with the qualification test results.
    - Valve: The SV and the IV share the same hydraulic design and therefore a unique model is used for both. The pressure drop was correlated with the acceptance test results of a typical valve.
    - Pyro-valve, normally open: Installed in the PCA outlet, is modelled as an orifice and the pressure drop is correlated with dedicated helium flow tests.
    - Orifice: Sets the gas flow by choking the flow. The mass flow rate is correlated with the acceptance test data.
- The data from the hydraulic model of the PCA, which was tested at the P2 test facility of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Lampoldshausen, is used to anchor the steady pressure drops across the PCA branch at the four locations P1, P2, P3 and P6.
- The error between the predicted and the measured pressure was reduced below 4% by tuning the pressure loss coefficients (Kf) and (ζ).



Layout of the model of the helium section of ESM-3.

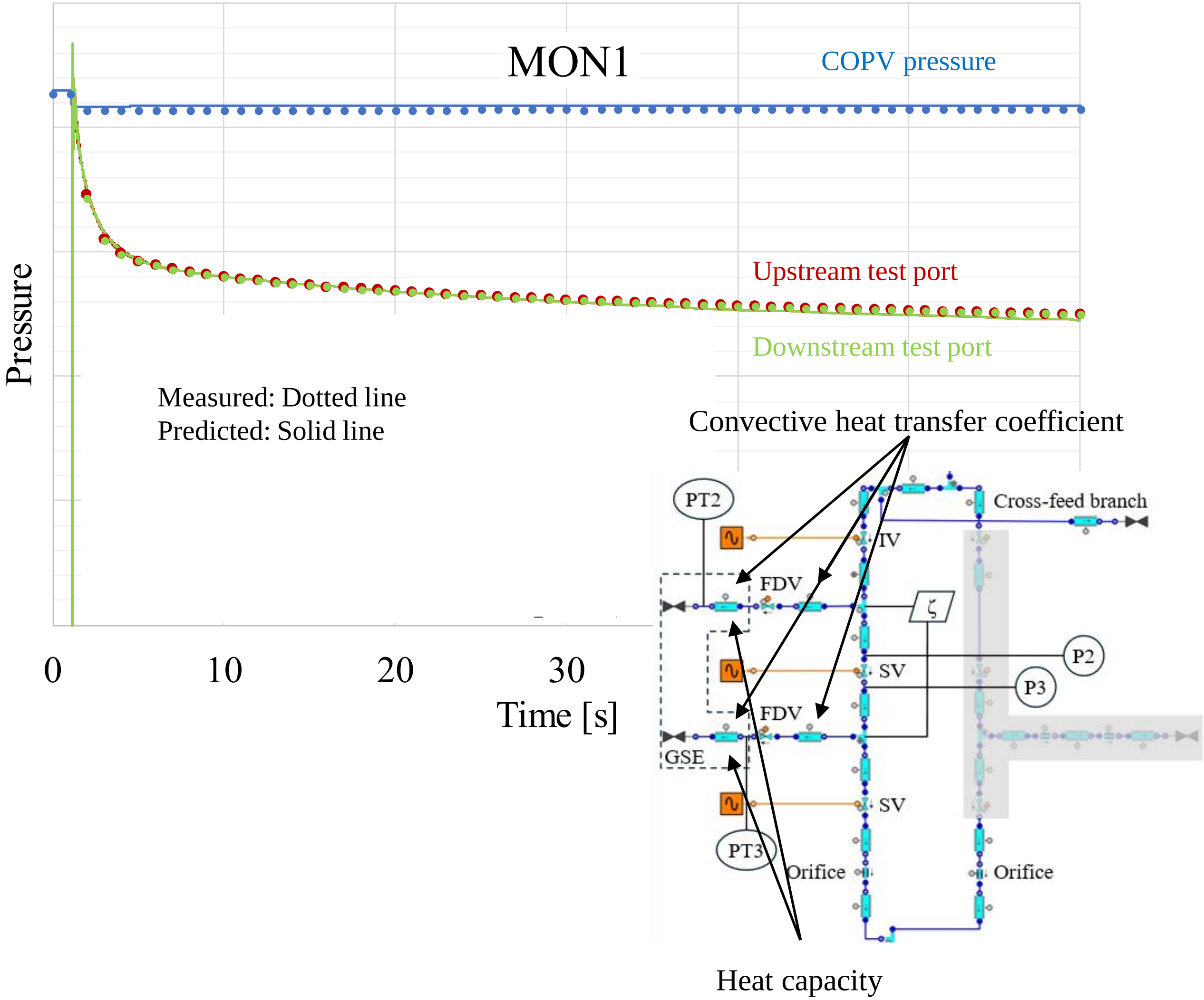
Model Validation

- During the coast phases, the PCA is exposed to helium saturated with propellant vapour.
- Flushing of the PCA branches with clean helium mitigates the risk of an elongated exposure to propellant.
- This highly transient sequence was exercised in the PCA hydraulic model and used to compare with the predictions by the numerical model.
- The response time of the valves is not resolved. Instead, the flow area of the valve is explicitly set to fully open or closed to match the onset of the pressure raise or drop.
- This is a valid approach since the response time scattering between valves would require anchoring the test data in any case.
- Moreover, the characteristic time of the valve – poppet – movement is at least one order of magnitude lower than the pressure transients of interest.
- The agreement between prediction and measurements is remarkably good.



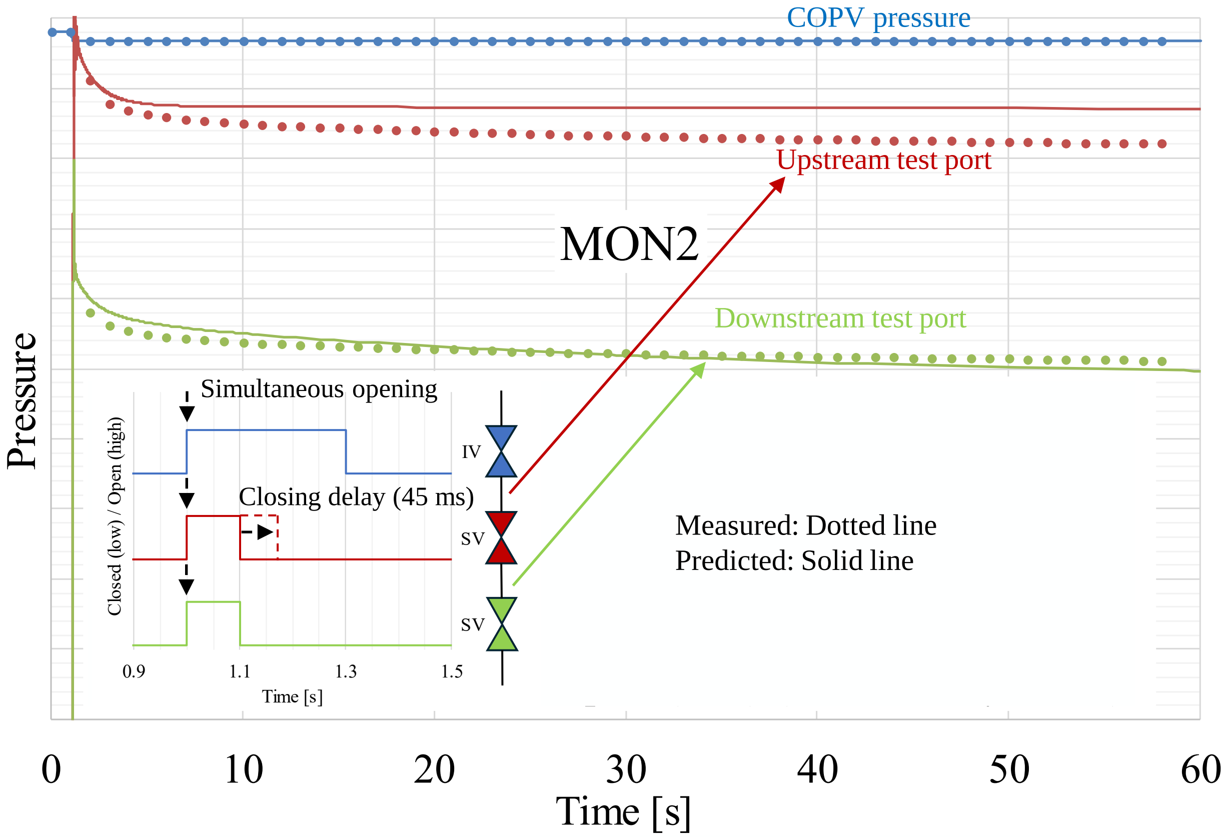
ESM-3 Test Assessment

- The thermal characteristics of the model were anchored to the observed pressure decay in branch MON 1 by optimisation of: the convective heat transfer coefficients from ambient to the test port lines and to the flexible (test) lines, and the heat capacity of the flexible lines.
- The upstream SV was held open in the simulation.
- The mean squared error between predicted and measured pressure at the locations of PT2 and PT3 was the optimization target.
- The narrow agreement with the predictions confirms that the observed pressure decay is thermally driven.
- The pressure decay is very pronounced in the instants following the valve closure, driven by the rapid cooling of the lines
- The prediction shows that the actual pressure differential when the IV closes may be considerably lower than measured, owing to the low acquisition rate of 1Hz.



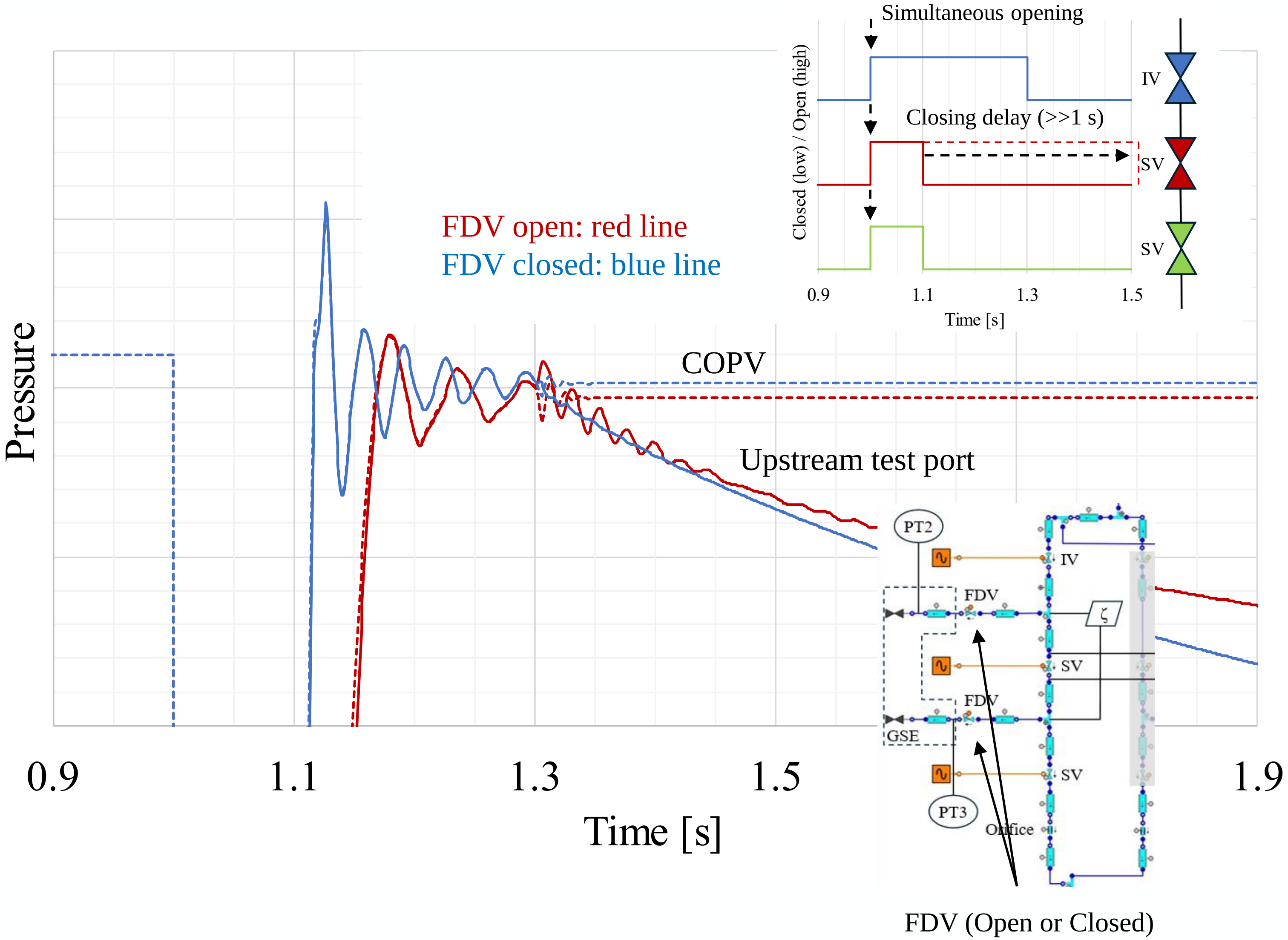
ESM-3 Test Assessment

- The opening delay of the valves does not affect the resulting test port pressure. Therefore, the three valves were assumed to open instantaneously when commanded.
- The predictions showed that the delayed closure of the upstream SV increases sensibly the pressure of the downstream test port.
- The closing delay of the upstream SV was estimated to be 45 ms on the MON1 branch (24 ms on MMH1).
- This was estimated by matching the downstream test port pressure at the end of the 60 s window.
- This outcome is in line with previous experiments showing that an open valve which has been slammed by a high-pressure inrush typically closes with delay when commanded.
- It reassures that the observed pressure decay is thermally driven.



ESM-3 Test Assessment

- The pressure oscillation in the upper test port volume remains under 0.3% at the time of closing the IV.
- The oscillation is even lower in-flight configuration with the test ports (FDV) closed.
- This confirms that the differential pressure builds up owing solely to the cooling of the test port downstream of the IV.



Conclusions

- The pneumatic model was correlated to match component and PCA test data at steady operating points of pressure and flow rate, predicted an excellent agreement with transient data. This confirms the adequacy of the underlying formulation.
- The pneumatic model allowed investigating the unexpected pressures in the volumes between valves, which were observed after executing the flush-prime sequence in the branches of the PCAs during the acceptance tests of ESM-3.
- The model confirmed that the differential pressures that were measured across the IVs were driven by thermal effects as the volumes within the valves cool down subsequently to the severe pressurisation.

Thanks for your attention

Questions?

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