Live Propellant Transient Test Results Achieved in the ExoMars Test Campaign

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Abstract

The ESA ExoMars mission is planned to start in 2016 with a scientific orbiter module and a demonstration descent and landing module. The long and complex mission resulted in a complex propulsion subsystem which needed to be validated through a series of tests.

The tests were performed on representative models and allowed to test the different flight conditions and operations such as the priming at the beginning of the mission or the thruster firing with the associated water-hammer. For the tests, both MON-1 and MMH propellants were used in saturated at 12 bar (flight-like) and unsaturated at 2 bar conditions. This allowed to compare the results and to determine the influence of the saturation on the priming and water-hammer pressure peaks.

This paper will present an overview of the test results for the priming and water-hammer results for MON-1 and MMH depending on the different parameter such as the vacuum level, the mass flow or the saturation level.

1. Introduction

The ESA ExoMars mission, planned to start in 2016, uses a complex and innovative bipropellant propulsion subsystem, especially in terms of the PIA (Propellant Isolation Assembly). The design had been previously simulated with EcosimPro, delivering results and giving guidelines on the operational approach. However, these simulations needed to be validated and correlated by test results.

The critical aspects of such simulations are the transient effects encountered during priming and water-hammer. These two effects are indeed very difficult to predict and simulate, especially given the nature of the propellant, whose physical characteristics are partially unknown, leading to uncertainties of up to 65%. In comparison, the same calculation using water as fluid leads to much more reliable results, with only 8% uncertainties in the peak predictions [1].

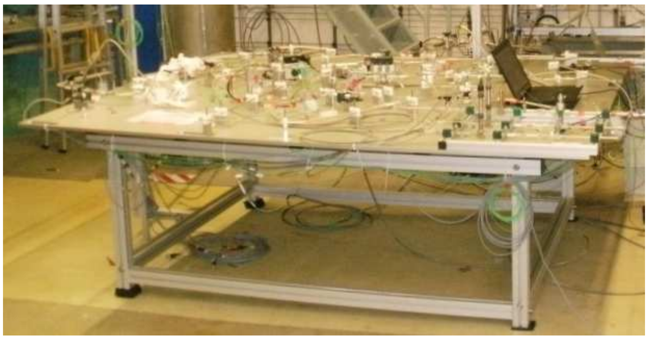

Figure 1 - EVM PIA Test Setup MMH

The lack of knowledge of the characteristics of the propellant is due to their hazardous nature, but also due to a very limited number of correlation points, i.e. available test data.

For that reason, the ExoMars EVM (Engineering Validation Model) test campaign was designed. It would make maximum use of live propellant MMH and MON-1, as well as integrate flight-like units for increased representativeness.

2. Test Objectives

The EVM test campaign had several objectives and was divided in a PCA and a PIA test campaign.

The primary objective of the EVM was to validate the numerical models to be used for prediction of the ExoMars design. This includes the measurement of the pressure drop and also the priming and the water-hammer tests with MMH and MON-1. As the two propellants have different characteristics, it is necessary to test both in order to get results for both sides of the PIA.

In order to achieve the primary objective, different measures were taken. One of them was to represent the ExoMars design in the EVM design as close as possible. This was a very important part of the EVM test since all the test results obtained needed to be analysed and correlated with mathematical models. To this purpose, a dedicated EVM model was produced. Once this model had been correlated, transposing the results to the ExoMars design model was just a small step. The details regarding the EVM design are presented in the next section. Another important measure was to make use of flight-like units wherever possible. To this purpose, a pyro-valve, a filter and all the thruster valves were present in the design. This improved greatly the confidence level in the test results obtained, especially combined with the representativeness of the ExoMars design.

A secondary objective was the validation of subsystem operation strategies to be used in the ExoMars. Indeed, due to the initial uncertainties coming from the mathematical model, it was hardly possible to assess on the hazards resulting from one or the other operation. Opening the valves in an inappropriate sequence could result in unexpected pressure peaks. Therefore, the EVM tests planned also to operate the different valves in alternate order.

3. Test Setup

While the test setup and its characteristics define the quality of the test results and the correlation, the ExoMars design is extremely large and complex as presented in Figure 2. Therefore completely replicating it for such a test would have been extremely costly. It was therefore decided to take the ExoMars design and build its most important features relative to the test objectives into the EVM test setup, as presented in Figure 3.

That meant testing the relevant mass flows of the mission, i.e. fire the Main Engine while operating up to six 10 N thrusters, in order to gather results for the water-hammer. Also, for the priming, it was necessary to build the longest thruster lines (Main Engine and 10 N thrusters) as this is a critical parameter for priming peaks, as well as the Fill and Drain Valve lines, which were also built. At the end of the 10 N thruster line, two valves were implemented, one 10 N valve to represent one thruster, and one 200 N valve to represent five 10 N thrusters with equivalent mass flow rate and therefore achieve the water-hammer test

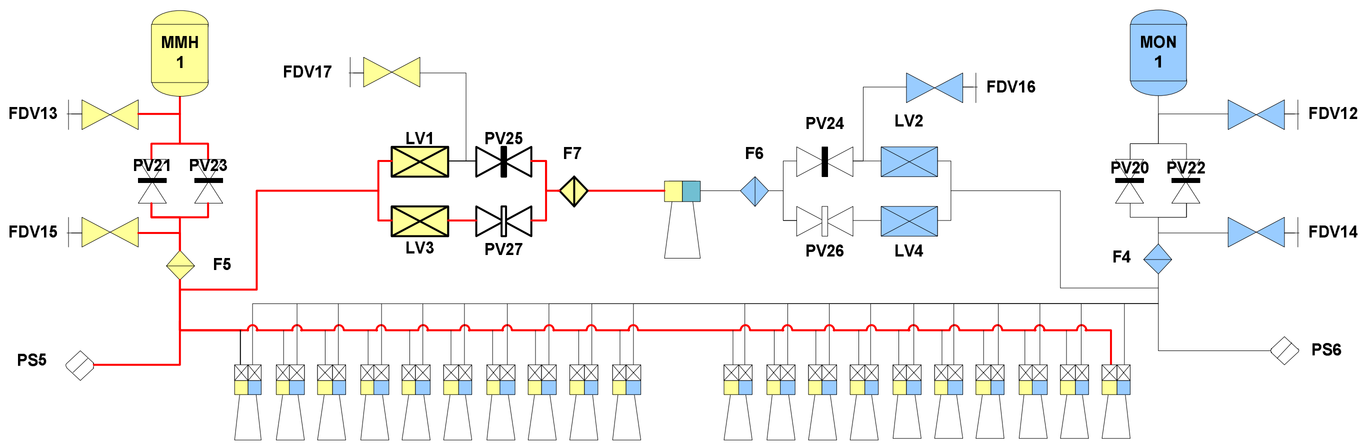

Figure 2 – ExoMars with the EVM PIA MMH in RED

objectives. All valves representing the Main Engine, the 10 N thruster and the five 10 N thrusters were actual flight valves with similar opening and closing time.

Due to the fact that the EVM test campaign included tests with both MMH and MON-1, two independent setups had to be built. This was a necessary decision due to the operational constraints associated with using the same setup for both propellant as well as to ensure the safety of the test site and its operators. This allowed also to adopt both test setup to represent at best the ExoMars design for both sides of the PIA.

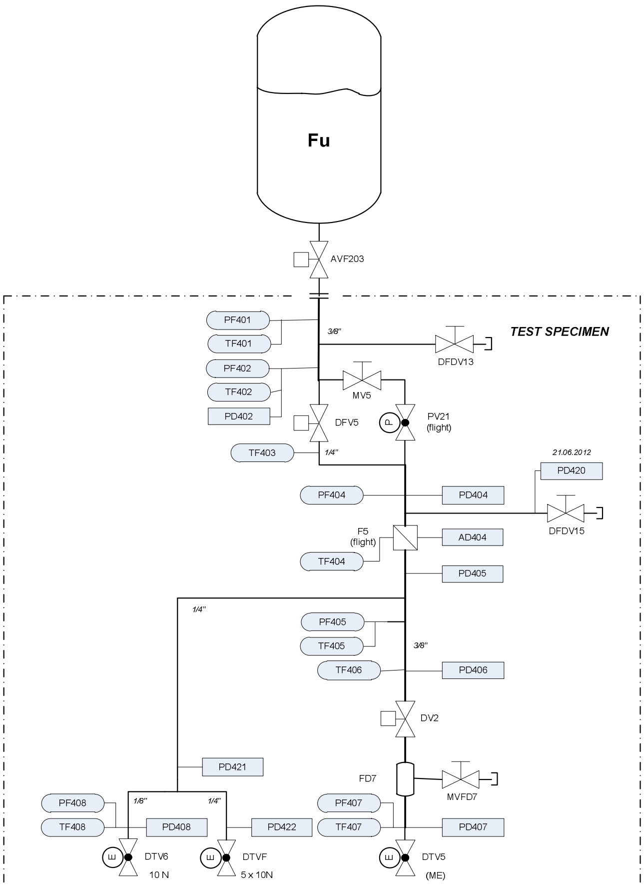

Figure 3 - EVM PIA MMH instrumentation

Regarding the Pyro-valves, it was not possible to use one for each test due to cost reasons, but also due to associated logistic of changing a valve in a contaminated system. Therefore, one Pyro-valve per test setup (MMH and MON-1) was integrated and used for the first priming test of each campaign. For the remaining tests, a DFV (Dummy Fast Valve) was used. These valves are ball valves with pneumatic actuators. Their opening speed were located around 50-60 ms. This was considered acceptable for the tests compared to the ca. 2 ms of the Pyro-valves.

Another very important part of the test setup was the measurement system and the different sensors implemented in the system. The EVM Test Setup was equipped with four different types of sensors:

- Acceleration
- Static Pressure
- Temperature
- Dynamic Pressure

There was only one accelerometer installed on the upstream flight filter. The purpose of this accelerometer was to measure the Pyro-valve shock and to see if any acceleration was detected during the priming and water-hammer processes.

The static pressure sensors were used only for the pressure drop measurements that were another part of the EVM tests, but not related to any transient behaviour.

The priming process is highly energetic and leads to quick gas compression. This creates temperature changes inside the tubing that had to be measured with temperature sensors placed on specific points on the tubing.

Finally, the dynamic pressure sensors are the most critical part of the measurement equipment. These sensors are necessary to detect any transient pressure behaviour due to their very small response time.

A special care was taken regarding the position of theses sensors in order to minimize the influence on the test results. For the acceleration and temperature measurements, this was not an issue as the sensors were placed on the outside of the tubing, therefore not in contact with the propellants MMH or MON-1. For the static and dynamic pressure sensors, these had of course to be in contact with the fluid in order to measure the pressure.

In addition, gravity had to be considered for the EVM tests. The priming process in orbit will have the propellant fill the lines starting with the surfaces following a capillarity process. However, on Earth, this is not possible and the propellant is filling the line over the full section at once. In order to limit the effects of gravitation, the whole setup was built horizontal (see Figure 1). This also influenced the position of the pressure sensors, which were therefore placed horizontal as well.

As already explained before, the EVM tests were performed with live propellants MMH and MON-1. For each propellant, the tests were in fact doubled in order to take into account the saturation level, which represents the maximum amount of Helium in solution within the propellant. This saturation level is mostly depending on the pressure at which the propellant is pressurized. During the ExoMars mission, the priming is planned to take place at the beginning of the mission, i.e. when the saturation level is located around 12 bar, the launch pressure. For a better correlation process a test with a much lower saturation level, i.e. 2 bar, was performed. The idea was to get a good sensitivity with respect to the diluted amount of gas, which was believed to be released and therefore damp the priming process. The gas used to pressurize and therefore diluted within the propellant was Helium, as it will be for the ExoMars mission.

4. Priming

The numerical analysis of the priming pressure peaks done previously showed confidence that there would not be any safety issue with regards to the priming peaks. Due to the associated effort to prepare the test setup for the priming test, only five priming test per propellant were performed, two of which with low saturated propellant.

Since there was only one Pyro-valve per setup, it was decided to use it for the first priming each time. This ensured the best test conditions in terms of dryness, residuals and vacuum. For the subsequent priming tests, the test setup needed to be drained of the propellant, then subjected to vacuum to evaporate the residuals. Once a sufficient vacuum level was achieved, the next priming test could take place.

4.1. Test Sequence

Before each test could begin, predefined initial conditions had to be reached. For the initial setup, all valves were to be closed, except for the Pyro-valve once it had been opened, which was isolated by an additional ball valve, and the Main Engine Latch Valve (DV2) that was opened, as this was the planned operation sequence for the ExoMars mission. However, the test PIA-8B was performed with this particular valve closed in order to test an alternate operating sequence.

Furthermore, the lines without propellant, i.e. to be primed, were to be free of propellant and under a vacuum of less than 10 mbar. This

	PIA-1	PIA-2	PIA-3	PIA-3B	PIA-4	PIA-5	PIA-6	PIA-7	PIA-8	PIA-8B	PIA-9	PIA-10
Propellant	MON-1	MON-1	MON-1	MON-1	MON-1	MON-1	MMH	MMH	MMH	MMH	MMH	MMH
Priming Valve	PV	DFV	DFV	DFV	DFV	DFV	PV	DFV	DFV	DFV & DV	DFV	DFV
Vacuum	1 mbar	7 mbar	9 mbar	7 mbar	9 mbar	7 mbar	2 mbar	8 mbar	3 mbar	2 mbar	4 mbar	9 mbar
Saturation	12 bar	12 bar	12 bar	12 bar	2 bar	2 bar	12 bar	12 bar	12 bar	12 bar	2 bar	2 bar

Figure 4 - EVM Priming Initial Conditions

condition was reached for each priming test and led to a very good comparability between the different test results. Finally, the tank would be pressurized with 12 bar Helium, representing the launch pressure of the ExoMars mission. With respect to the saturation level, the propellants would be stored under the saturation pressure, and in the case of the 2 bar saturated propellant, be only pressurized a few minutes before the priming. This way, the saturation level would not increase for the test.

Figure 4 presents these initial conditions for each priming test performed. Please note that the test PIA-1 to PIA-5 refers to the priming tests performed with MON-1 and PIA-6 to PIA-10 to the ones performed with MMH. Please note also that the valve and sensor numbers given throughout this paper reflect the flow schematic presented in Figure 3, which represents the MMH test setup.

The test sequence for the priming test was very simple once these initial conditions were achieved. The steps for the priming were the following:

1) Reach initial conditions
2) Pressurize tank to 12 bar
3) Open priming valve
4) Wait for stabilisation

Considering that the priming peak needed about 2 seconds between the opening of the valve and the moment when the peak occurred, the stabilization duration was always at least 30 seconds.

During the PIA-8B priming test, the sequence was modified in order to test an alternate operating sequence. During this test, the steps were the following:

1) Reach initial conditions
2) Pressurize tank to 12 bar
3) Open priming valve
4) Wait for stabilization
5) Open ME LV (DV2)
6) Wait for stabilization

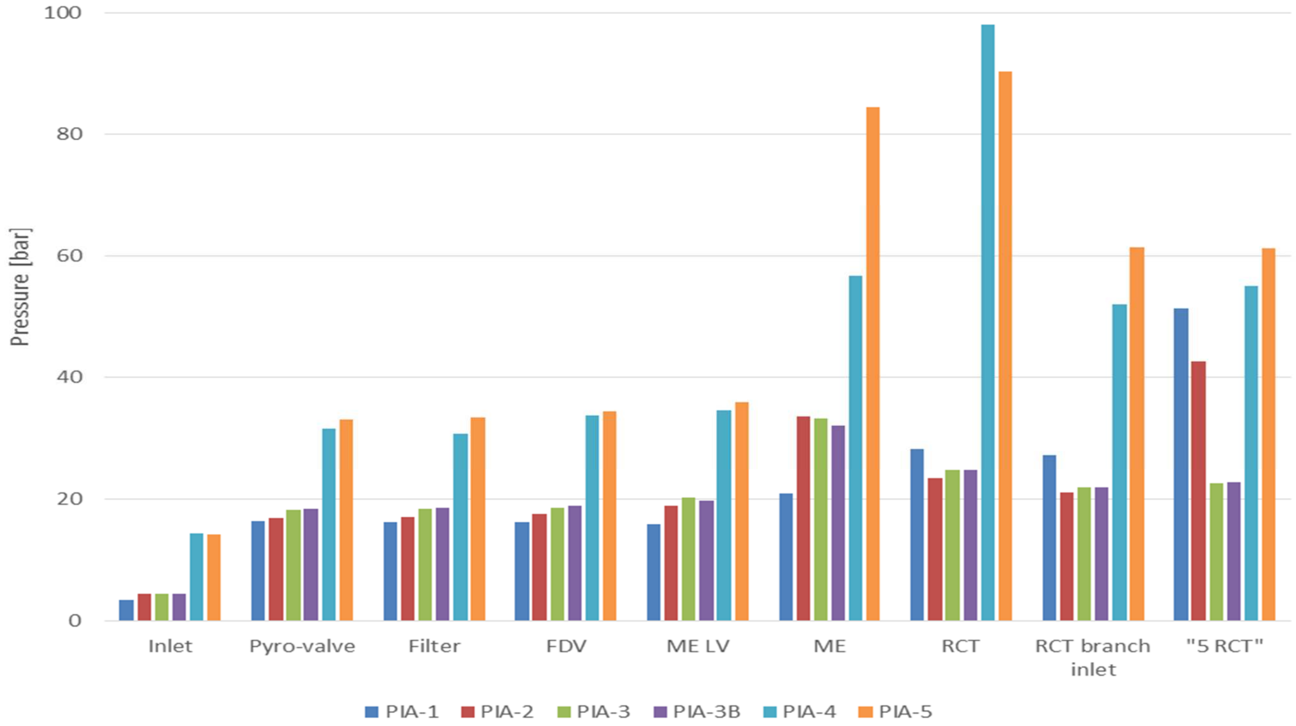

Figure 5 - EVM PIA MON-1 Priming Results

In this sequence, the priming was performed in two steps. During the first one, the lines were primed with the exception of the Main Engine which was isolated by the ME LV valve. This valve was of the same type as the DFV valve with the same range of opening speed. In the second step, the priming would be finished down to the Main Engine valve by opening the ME LV valve.

4.2. Test Results

The EVM priming test results gave insights regarding the height of the priming peaks, their location, their duration as well as the influence of the saturation level. First of all, the raw values of the height of the priming peaks indicate different information. For the MON-1 tests, the results are presented in Figure 5, and for the MMH in Figure 6.

The most obvious result from the MON-1 tests, is the influence of the saturation level of the propellant. The tests performed with a saturation level of 2 bar show priming peaks values of 50% to 300% higher than with a 12 bar saturation. The reason for this is the dissolved helium in the propellant.

During the priming process, the propellant pressurized at 12 bar, comes in contact with vacuum. At this point, the propellant vaporizes and helium is released resulting in the creation of a gas bubble, which size mainly depends on the vapour pressure and the quantity of gas diluted within the propellant. This gas bubble will remain in the lines and cannot be absorbed by the propellant before the end of the priming process. When the propellant is filling up the lines down to the thrusters, this bubble will serve as a damper by compression of the gas.

In the case of the MMH, this conclusion can also be derived from the test results, however at a lesser degree with a difference in the peak values in the order of 50% maximum. This can be explained by two factors related to the physical characteristics of the propellants. First, MMH has a much higher vapour pressure than MON-1. This makes the vaporization process less effective on MMH and therefore limits largely the amount of gas

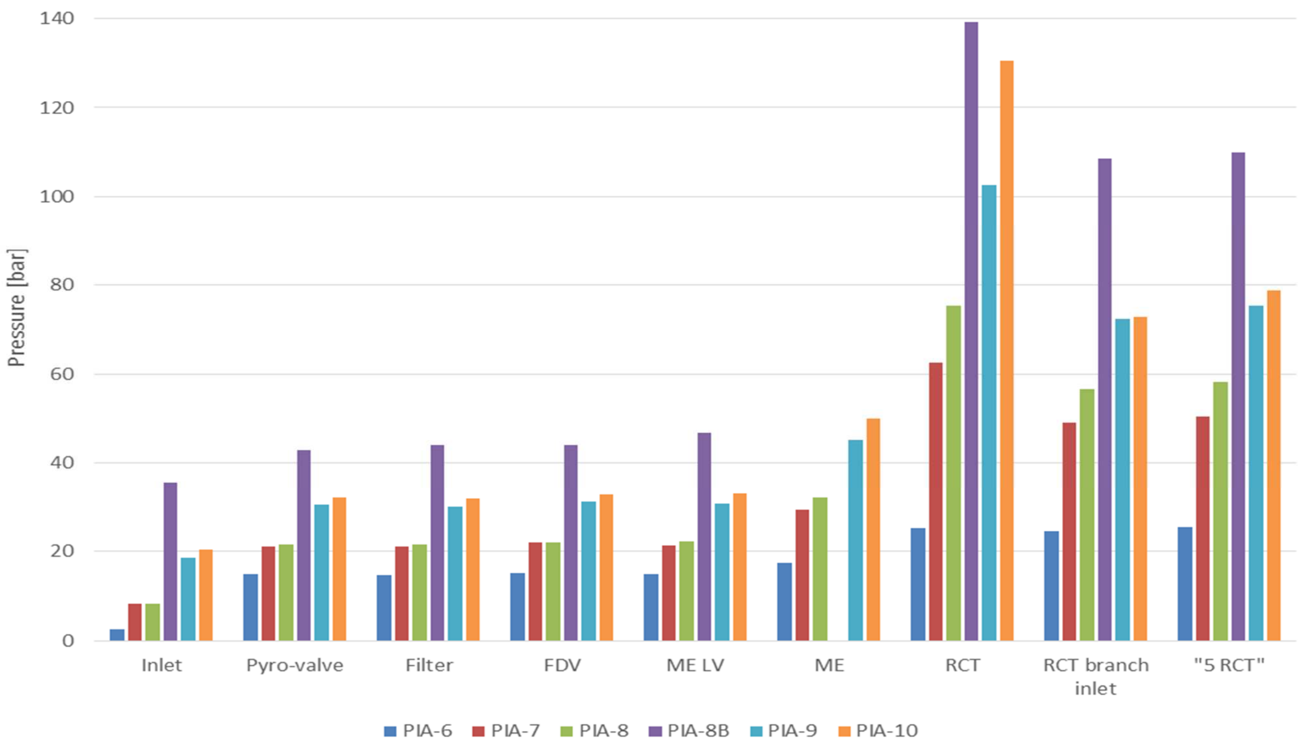

Figure 6 - EVM PIA MMH Priming Results

released. Secondly, MMH can absorb far less gas than MON-1 at the same pressure, reducing even further the amount of gas released.

It is important to note the dispersion in the test results with 2 bar saturated propellant both MON-1 and MMH. This occurs only with the highest pressure peaks and could be associated with a secondary order process, only triggered when the priming energy reaches a certain level.

A second result that can be deduced from the test data concerns the location of the peaks. As expected these are only located at the ends of the lines (ME and RCTs), were the propellant finishes to fill the lines during the priming process. The resulting peaks at any other location are only a damped and bounced derivate of this initial peak. This is confirmed by the fact that the height of the peak decreases with the distance from the ME and RCTs, i.e. the lowest peak can be found at the inlet of the PIA.

A third insight is the impact of using a Pyro-valve compared to a Dummy Fast Valve. As explained before, the opening time difference between the two types of valve is quite large with ~ 2 ms for the Pyro-valve and 50 to 60 ms for the DFV. It was expected that the results would show higher peaks with the Pyro-valve, even if not significantly higher. But the results were quite surprising.

For the MMH priming test with the Pyro-valve, the peaks are lower at all locations, especially the ME and RCTs. When looking at the priming peaks duration, it appears that they are relatively long, 30 to 50 ms. In comparison, the priming peaks measured using the DFV lasted a maximum of 10 ms. This tends to prove that there was much more gas in the line during the Pyro-valve priming test, which damped the peaks and made them last longer.

For the MON-1 tests, the Pyro-valve priming peaks are lower in the upstream section and on the ME, however, they are higher on the RCTs. This discrepancy was also observed during the

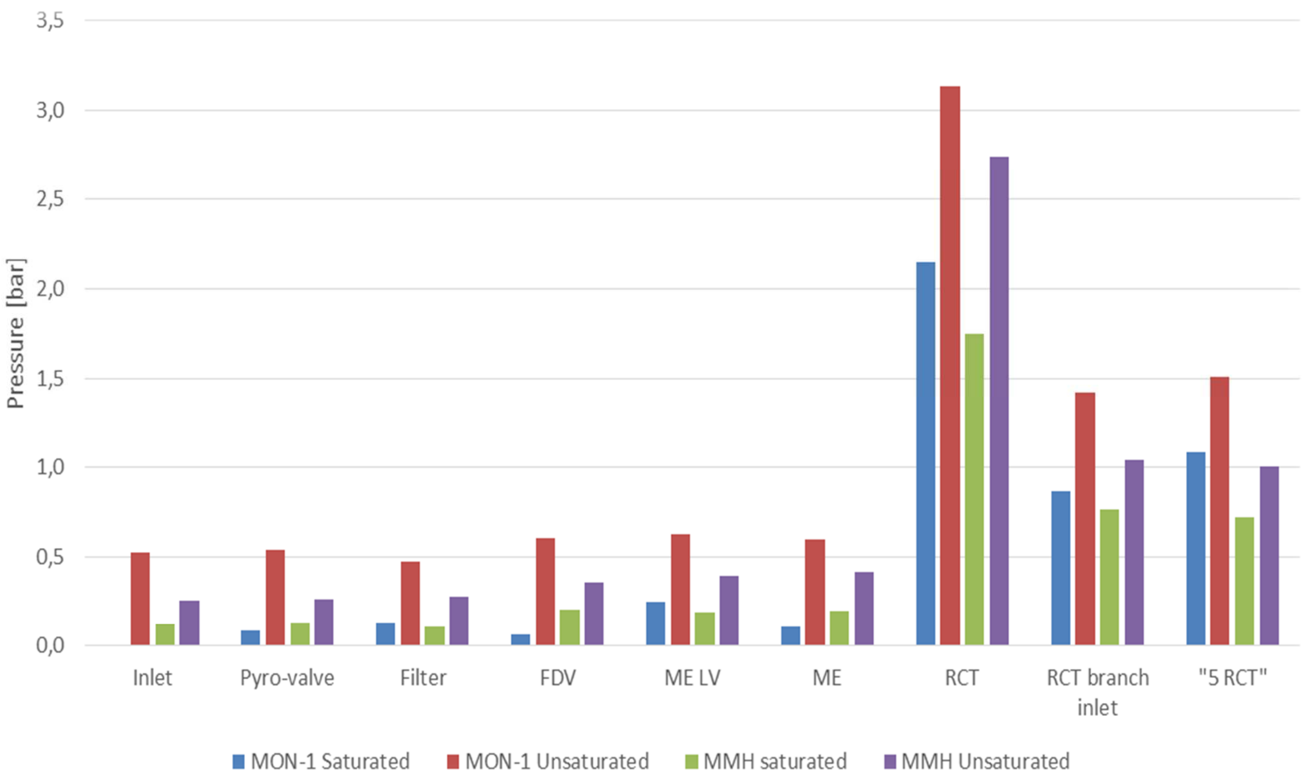

Figure 7 - EVM PIA 1 RCT Water-Hammer Test Results

first priming test with the DFV (PIA-2). The same difference in terms of peak duration can be observed in both cases, which tends to demonstrate that there was also more gas in the lines. Regarding the PIA-2 case, a further analysis of the priming “acceleration”, i.e. priming peak divided by peak duration shows that the three tests performed with DFV and 12 bar saturated propellant have the same “acceleration”. This demonstrates that even though the peaks and duration were different, the energy involved was similar. This “acceleration” is always the lowest for the Pyro-valve priming, enhancing the idea that there was more gas in the lines, and also 10 to 20 times higher when using propellant saturated at 2 bar compared with propellant saturated at 12 bar.

Regarding the difference observed for the Pyro-valve, a possible explanation is that the Pyro-Valve would be a damper. Indeed, due to the very high opening speed of the valve, a much larger quantity of propellant comes in contact with vacuum at the beginning of the priming process. At this stage, all this propellant will outgas its solute Helium. However, once this first instant has passed, this quantity of gas would be in fact more than required to achieve an equilibrium state during the priming process until the lines are filled. With a slower valve, only the necessary amount of gas to achieve the equilibrium would be released. In this theory, the difference observed between MON-1 and MMH would support this, given the much lower vapour pressure and higher Helium solubility of MON-1. In this case, even with a slower valve, the amount of gas released would approach the Pyro-vale one, even though it will not reach it.

Concerning the PIA-8B test, it is important to notice the influence of having the ME LV closed during the priming. In this case, a peak of ca. 140 bar was measured on the RCT, making it by far the worst case, reaching even higher pressure than with 2 bar saturated propellant. This can be easily explained by the volumes available. When the ME LV is closed, all the ME line is not available. Therefore, all the propellant and its energy are diverted to

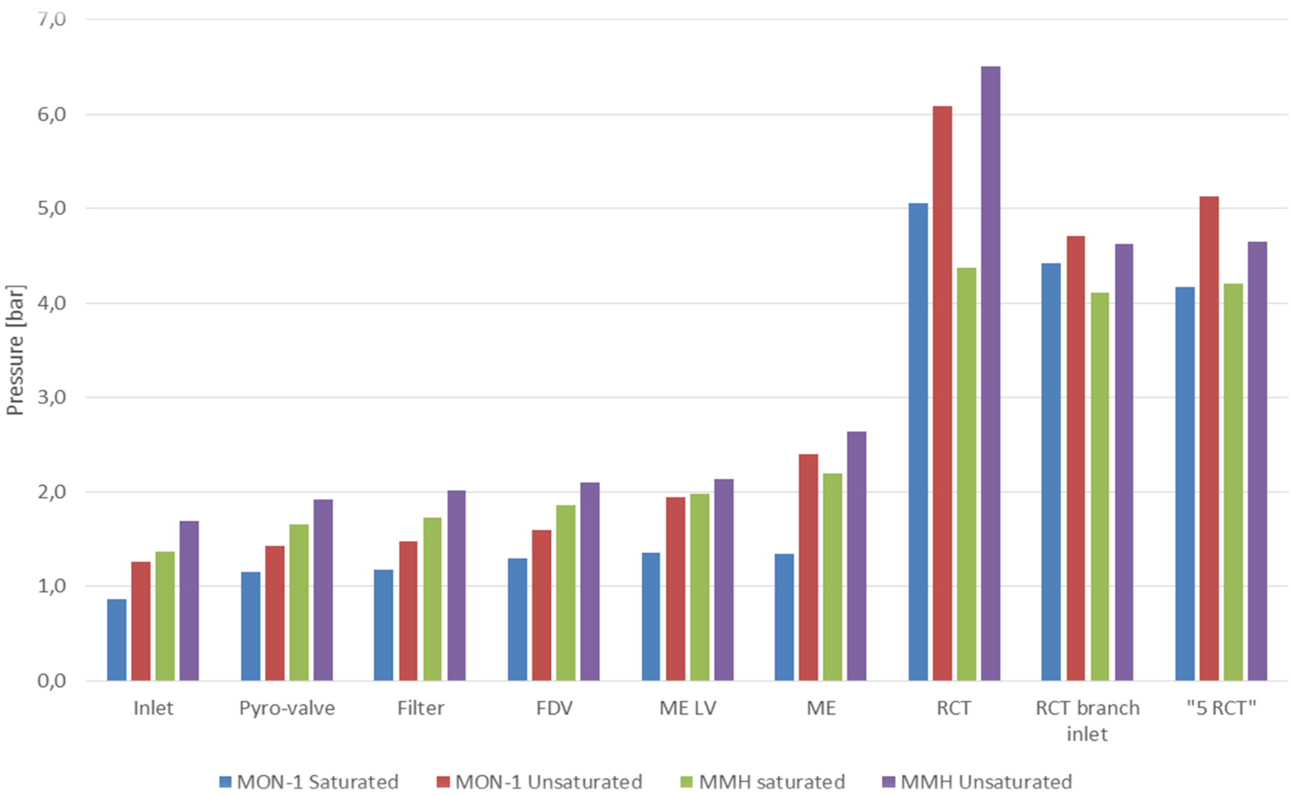

Figure 8 - EVM PIA 6 RCTs Water- Hammer Test Results

the RCT line, leading to much higher priming peaks. This shows how the number of branches impacts directly the priming peaks.

5. Water-Hammer

The water-hammer tests were the second part of the EVM PIA test performed on each test setup for MON-1 and MMH. After each priming test, once the lines were filled with propellant, the setup was used to perform water-hammer measurement, leading to an extensive set of test results.

5.1. Test Sequence

The test sequence of the water-hammer tests was the same for both MMH and MON-1 propellants. With regards to initial conditions, there were only two constraints.

First, the lines had to be primed and free of gas bubbles. The primed status was automatically achieved since the water-hammer tests were performed after the priming tests. Regarding the bubble free propellant, the solution was to purge the lines for ca. 30 s with all thruster valves in order to evacuate the potential bubbles from the system.

Secondly, the water-hammer tests needed to be performed at MEOP in order to be representative of the ExoMars mission. For this reason, the EVM supply pressure was raised to 18 bar before starting any water-hammer tests.

Regarding the test sequence itself, the water-hammer tests followed this sequence:

1) Open RCT + “5 RCTs” valves
2) Close RCT + “5 RCTs” valves
3) Open ME + RCT + “5 RCTs” valves
4) Close ME + RCT + “5 RCTs” valves
5) Open RCT valve
6) Close RCT valve

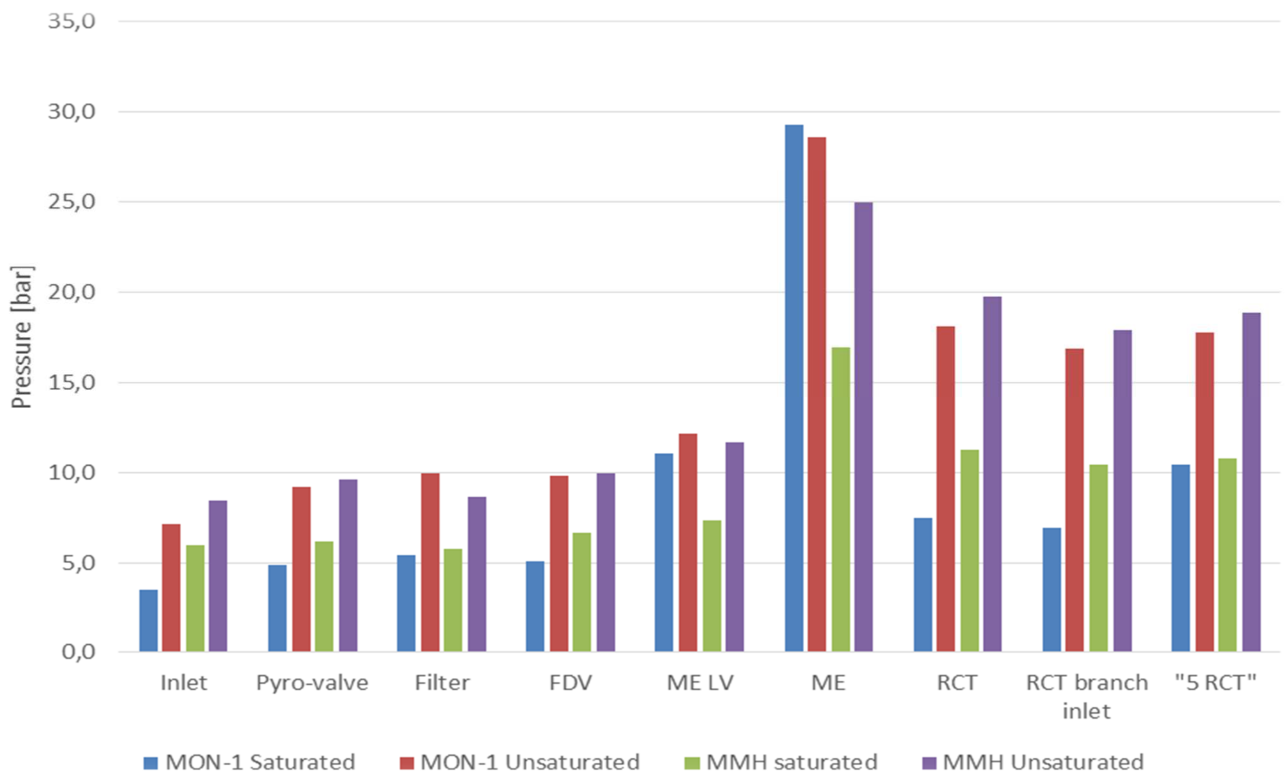

Figure 9 - EVM PIA ME + 6 RCT Water-Hammer Test Results

With this test sequence, three different water-hammer tests were performed, depending on the mass flow of the different thrusters. This diversity in test allowed to gather extensive measurement data which was precious for the correlation of the numerical models. As explained previously, the valves used for the ME, RCT and “5 RCTs” were flight-like valves, therefore producing flight-like test results.

5.2. Test Results

The results of the water-hammer tests are presented separately for each different mass flow configuration. The results for one RCT alone are presented in Figure 7, for six RCTs (one + five) in Figure 8 and for the ME and six RCTs in Figure 9.

These results are very positive and show a very good coherence. Different conclusions can be drawn from these results, regarding the intensity of the water-hammer as well as the location at which the highest peaks can be expected. Regarding the position of the peaks, it can be observed from the three figures presenting the results that the maximum peaks are located at the ME and ME LV when the ME is activated. When the ME is not fired, the maximum peaks are also located at the RCTs. However, these peaks are very small, with a maximum of 5 bar, making the water-hammer with RCTs only negligible. In case the ME is also fired, the peaks are much higher, with maximum reaching almost 30 bar at the ME LV.

6. Conclusion

In conclusion, the following can be derived from the test results obtained during the EVM PIA test campaign:

- Gas saturation has a large influence on the height of the priming peaks
- Slower opening speed of the valve doesn’t decrease the priming peaks.
- The priming peaks are maximum at the thrusters (RCTs and ME)
- The water-hammer peaks are maximum where the biggest thruster is fired
- The number of branches impacts the priming peaks

Regarding the possible damping effect on the priming peaks of the Pyro-valve, further tests would be necessary to confirm this theory.

Acknowledgments

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