Fluid transient simulation for the ExoMars bi-propellant propulsion subsystem

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ABSTRACT

OHB System AG has developed the Mars orbiter propulsion system for the European ExoMars 2016 mission. The ExoMars propulsion module is a bi-propellant pressure-regulated system.

Complex transient phenomena occur in the propulsion system during the system activation (priming process) and during the thruster operations (water-hammer effects). Priming or water-hammer effects can lead in worst case scenario to a failure of components or of the whole system. In order to minimize the risks of this happening and to investigate these phenomena, a hardware test bench has been built, called Engineering Validation Model (EVM). The transient flow effects will be measure on this EVM. The EVM test bench consists of the Propellant Isolation Assembly (PIA) on which priming and water hammer tests were conducted using live propellants MON and MMH. At the same time, a numerical investigation based on models created in EcosimPro simulation tool has been performed. EcosimPro is a 1D object oriented simulation tool capable to simulate both priming and water-hammer phenomena.

INTRODUCTION

The propulsion subsystem of the Exomars orbiter is a bi-propellant pressure-regulated system, using MON-1 and MMH as propellants and helium as pressurant gas. High thrust manoeuvers are performed by a 400N main engine (ME). In addition to that, 20 reaction control thrusters (RCTs) with 10 N thrust each, are used for orbit correction manoeuvers, station keeping and support to the main engine during high impulse manoeuvers. Ten of the RCTs are nominal, backed-up by 10 redundant thrusters.

Figure 2 show Exomas propulsion subsystem during integration to the spacecraft. The detailed flow schematic of the subsystem is presented in Figure 3.

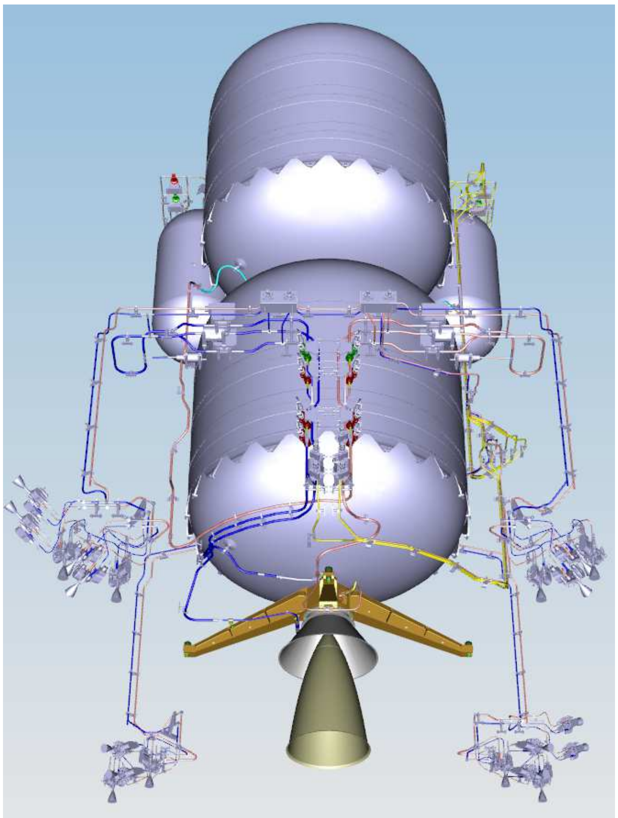

Figure 1: 3D-CAD-Model of Exomars PFM propulsion subsystem

Helium is stored in two 90 L tanks, and routed to the propellant tanks through the pressurant control assembly (PCA). The main PCA components are the pressure regulator (redounded), which allows to control the propellant tank pressures during long manoeuvers, and 2 sets of check valves, one on each branch (MON an MMH), to avoid propellant vapors to come into contact and cause unwanted chemical reaction in the PCA. The pyro-valves and the latch valves are used in order to comply with the relatively complex mission operation scenario and consequent reliability requirements. [1]

Figure 2: ExoMars during Integration at OHB

Propellant tanks are 1209 L each and feed the main engine and RCTs through the propellant isolation assembly (PIA). The main component of the PIA is the latch valve on the main engine branch, which isolates the main engine from the propellant, on ground and between manoeuvers.

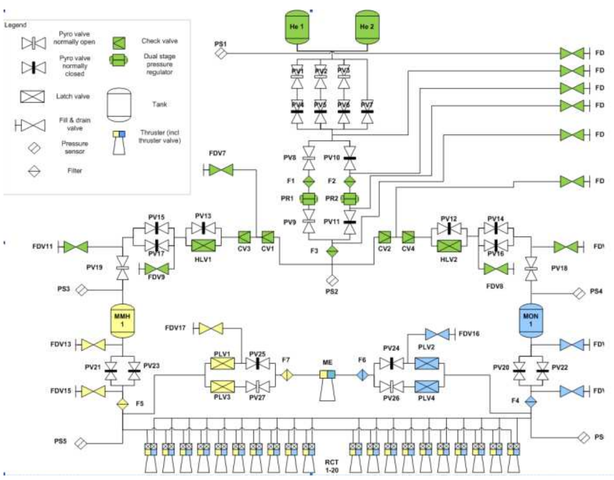

Figure 3: Flow schematic of the ExoMars propulsion subsystem

As shown in Figure 1, the helium tanks and the PCA are accommodated at the top of the spacecraft, and the PIA, main engine and RCTs at the bottom of the spacecraft. MMH tank is at the top and MON tank at the bottom.

The activation and operation of propulsion system lead to transients phenomena such priming (by filling initially evacuated tubing parts downstream of isolation Pyro Valves) and water-hammer (by closing of thrusters' valves or latch valves during operations). These effects lead to short-term pressure increase in propulsion system lines. It can damage or destroy propulsion components like valves, filters or tubing. To predict pressure surge in propulsion system, a test setup for experimental investigation of priming and water-hammer phenomena has been build up. This test is also used to measure the pressure drop in the system.

To support experimental investigation, a numerical investigation of transients in propulsion system has been performed. Results have been compared with experimental data, which will be presented below.

Simulation tool EcosimPro with ESPSS v2.4 libraries has been used for numerical investigation. EcosimPro is 1-D object oriented simulation tool developed by EA International for modeling simple and complex physical processes in terms of solve differential-algebraic equations and discrete events. ESPSS is a library developed for EcosimPro environment to model the complete propulsion system.

VALIDATION WITH TESTS FOUND IN LITERATURE

In the first step of numerical investigation of transients, a validation has been performed with data found in literature describing priming tests done with different fluids and on simple test branches. For this reason, a model in EcosimPro has been built with settings taken over from test setups described in public literature. In the simulation, the same initial conditions have been used. Figure 4 show used validation model for simplified test setups.

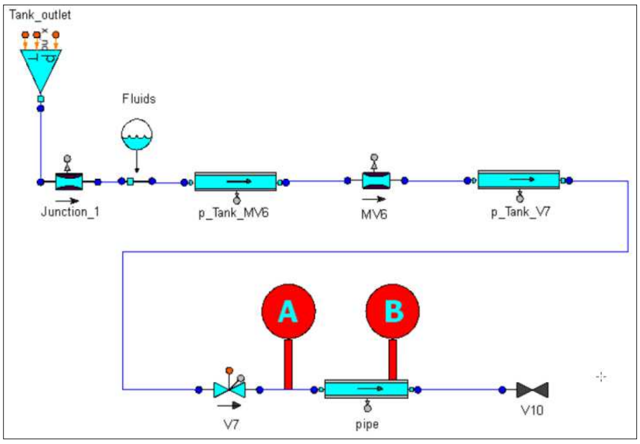

Figure 4: EcosimPro model of test setup described in [2]

Table 1 compares simulation results with experimental data. It can be seen a relatively good correlation with water (small deviation from experiment), but big deviation for propellants.

Fluid 1 [-]	Fluid 2 [-]	max pressure priming calculated [bar]	max pressure priming messuared [bar]	Deviation [%]
real H2O	perfect N2	312.9	289	8.3
real H2O	perfect N2	312.9	289	8.3
real H2O	perfect N2	297.08	289	2.8
real MMH	perfect N2	360	252	42.9
real NTO	perfect N2	301.4	252	19.6

Table 1: Comparison between simulation and experimental for priming [2]

Similar results can be observed by priming validation with data found on public literature done on the same test setup presented above. Simulation shows in this case also big deviations to experiment with propellants but good analogy between numeric and experiment for water and ethanol.

FLUID 1	FLUID 2	P initial	pipe type	max. pressure calculation	max. pressure messuments	Deviation
[-]	[-]	[bar]	[-]	[MPa]	[MPa]	[%]
real Ethanol	perfect N2	0.010	straight pipe	233	256	-9
real Ethanol	perfect N2	0.010	straight pipe	228	246	-7
real Ethanol	perfect N2	0.090	straight pipe	206	231	-11
real Ethanol	perfect N2	5.0	straight pipe	26	26	-1
real Ethanol	perfect N2	0.010	bend pipe	246	225	9
real Ethanol	perfect N2	0.096	bend pipe	228	214	7
real Ethanol	perfect N2	5.2	bend pipe	26	26	2
real MMH	perfect N2	0.010	straight pipe	409	301	36
real MMH	perfect N2	1.0	straight pipe	63	68	-8
real MMH	perfect N2	4.3	straight pipe	27	24	11
real MMH	perfect N2	0.010	bend pipe	459	279	65
real MMH	perfect N2	0.010	bend pipe	449	289	55
real MMH	perfect N2	1.0	bend pipe	79	61	30
real MMH	perfect N2	1.0	bend pipe	81	64	26
perfect MMH	perfect N2	0.010	bend pipe	305	289	5
perfect MMH	perfect N2	1.0	bend pipe	78	61	28

Table 2: Comparison between simulation and experimental for priming acc. to [3]

The reasons for big deviation by propellants can be that properties of MMH and MON-1 under different pressure conditions (from vacuum to critical pressure) are not very well known today (s. ref. [4]). Therefore, propellant properties are usually very roughly represented in commercial programs like EcosimPro. These properties are not valid for big pressure and temperature range as is the case for priming processes. Good correspondence between the simulation and the measurements for water supports this hypothesis.

The second reason for big deviation can be the influence of solved none-condensable gas in propellants that resolved by suddenly pressure decrease during priming processes and can lead to damping effects on priming shock level. There are no possibilities to consider helium solubility in used version 2.4 of ESPPS library and so this effect could not been modeled during study described above. Furthermore, in the simulation, the effect of chemical decomposition that can occur by MMH during priming compression approach is not included. This can generate gases which can also damp priming shock.

EXOMARS EVM TEST SETUP

To be sure in reliability of ExoMars propulsion system, the system has to be tested on ground. For these objectives, EVM (Engineering Validation Model) test campaign has been foreseen. The goal of test campaign was also the validation of numerical models to be used for prediction of the ExoMars flight model.

Because of propulsion system complexity and for deduction of test costs, the system has been divided to three full independent parts PCA (helium path from pressure regulator to propellant tanks), PIA-Ox (tubing line from oxidizer tank to thrusters) and PIA-Fu (line from fuel tank to thrusters). The propellant test setups have been built in horizontal orientation to limit the gravitation influence. Tubing design in view of bends, lengths and dimensions was consistent with flight model.

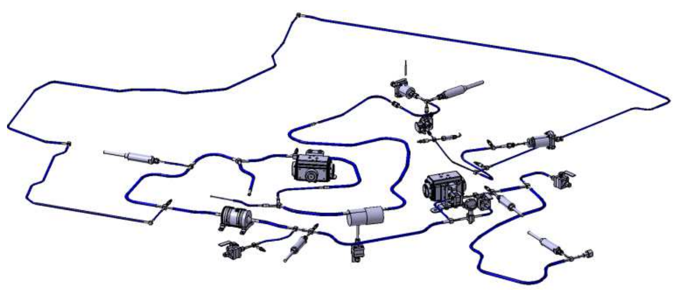

Figure 5: CAD model of PIA oxidizer test branch

Figure 5 show PIA oxidizer test branch with test components and pressure sensors.

The PIA part test campaign has been split in steps to investigate following objectives:

- priming of PIA, measure pressure and temperature change during priming process
- measure static pressure an several position and steady state flow rate

Several static and dynamic pressure sensors have been implemented on different positions of PIA test line. Figure 6 shows location of sensors in test line. Fast compression process during priming leads to temperature increase. To observe this effect, temperature sensors on different positions on the tubing have been placed.

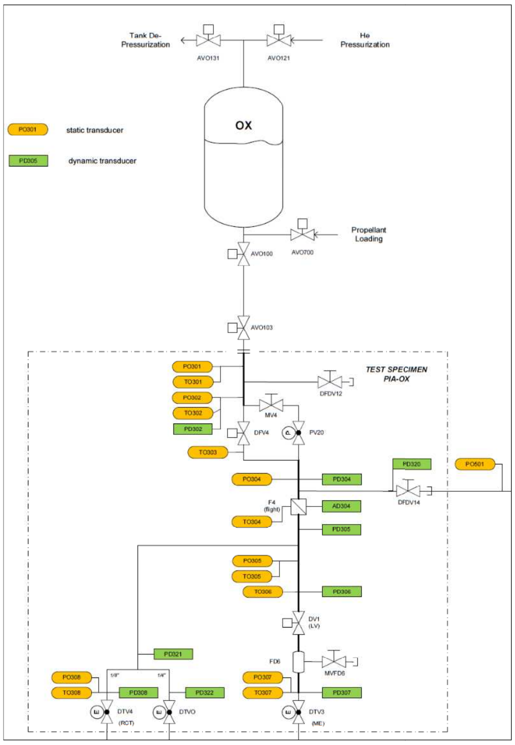

Figure 6: PIA oxidizer (MON-1) instrumentation

Dynamic and static pressure sensor were used for measurement of pressure evolution during priming process. For pressure drop measurements, only static pressure sensors have been used. PIA setup and measurements procedure has been described in details in [5].

NUMERICAL ANALYSIS

To support experimental investigation, numerical investigation of transients in propulsion system has been performed. The ESPSS libraries in EcosimPro environment has been used for modeling and simulation of ExoMars EVM tests. ESPSS libraries provide palettes of components represented by symbols that can be used to build graphically complex systems. ESPSS has been developed specially for modeling of rocket and satellite propulsion systems by solving time dependent 1D Navier-Stocks-Equations [6].

PIA oxidizer and fuel test setups have been modeling in EcosimPro environment. Two models in EcosimPro have been built up for this reason. Figure 7 show model of PIA oxidizer test branch. The pressure change has been observed in model at positions corresponding to test setup. The naming of pressure sensors was the same.

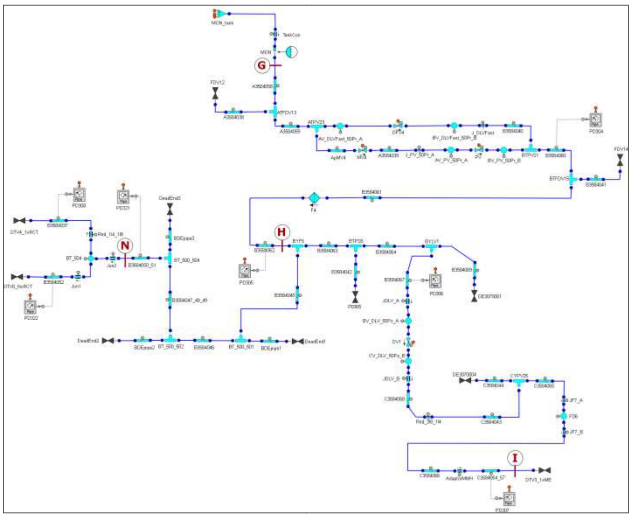

Figure 7: EcosimPro model of PIA oxidizer test setup

Priming test has been repeated four times during test campaign for MON-1 and so there are available several experimental maximal pressure peak values. Table 3 show measured and calculated pressure peaks.

		Experiment [bar]	Simulation pressure peaks [bar], case Nr.							
Sensor	PFM Equivalent	mean	1	2	3	4	5	6	7	8
PD302	PIA Inlet	**16.23**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PD304	Pyro-Valve	**17.44**	17.1	27.6	16.5	24.3	14.3	16.5	13.4	66.0
PD305	Filter	**17.53**	17.2	28.8	17.0	15.0	14.6	34.0	13.5	66.4
PD306	Main Engine Latch Valve	**18.72**	19.7	33.0	18.0	16.2	15.4	14.3	13.8	68.2
PD307	Main Engine	**29.96**	n.a.	54.3	24.0	19.0	17.4	15.5	14.7	212.7
PD308	RCT	**25.29**	161.4	63.2	31.8	15.0	20.1	16.7	15.5	302.9
PD320	FDV	**17.78**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PD321	RCT branch inlet	**23.02**	74.6	61.0	30.5	22.3	19.6	16.5	15.3	116.0
PD322	"5 RCTs"	**34.84**	75.7	62.0	32.0	14.8	20.1	16.8	15.5	132.6

Table 3: Measured and calculated pressure peak during priming on oxidizer side

Total eight simulation cases have been performed for oxidizer. To adjust simulation results has been developed damping factor in modeling, because validation cases on simple test geometry showed big deviation from experiment as described above.

There are possible to consider two fluids in ESPPS by modeling at the same time, the main fluid as propellant and second fluid as none condensable gas (pressurant). In our case pressurant was helium. In priming cases the high pressure tubing part is filled full with the propellant and evacuated tubing part (vacuum part) contain typically residuals of pressurant by small pressure. Helium as second fluid has been considered in all simulation cases with the oxidizer except of case 8. It has been assumed in case 8, that evacuated tubing part is filled with propellant vapours by low pressure. It can be seen from results presented in Table 3 that predicted pressure peaks overestimated on all pressure sensors by modeling with only one fluid. The highest peak on pressure sensor PD307 that represent Main Engine Valve in test setup, is about 6 times greater as measured value. In this case simulation time could be significantly reduced from about one week to one day, but predicted maximum pressure and peak time is far away from experimental values.

Fluid REAL NTO has been used as propellant in considered cases for MON-1 side because actually there is available MON-1 properties only as perfect fluid in ESPSS properties data base and this data are not sufficient for priming simulation. At the same time available physical properties don't cover all pressure range in priming process as it was discussed above. This fact did simulation unstable and calculation was crashed from time to time (results marked as *n.a.* are not available in Table 4).

For the EVM PIA fuel test setup has been built second model in EcosimPro environment. Figure 9 show used model for MMH branch. Location of all pressure sensors in the model is in according with test setup.

								Pressure sensor						
case	FLUID 1 (propellant)	FLUID 2 (pressurant)	P tank	T tank	opening time	open time	total sim. time	PD304	PD305	PD306	PD307	PD308	PD321	PD322
[-]	[-]	[-]	[bar]	[°C]	[ms]	at [s]	[hr]	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec
1	real NTO	perfect He	12.3	18	2	0.1	158.6	17.1	17.2	19.7	n.a.	161.40	74.6	75.7
								1.56	1.564	1.5622	n.a.	1.559	1.559	1.560
2	real NTO	perfect He	12.3	18	2	0.1	162.0	27.6	28.8	33.0	54.3	63.2	61.0	62.0
								2.007	2.007	2.008	2.010	2.021	2.021	2.021
3	real NTO	perfect He	12.3	18	2	0.1	142.6	16.5	17.0	18.0	24.0	31.8	30.5	32.0
								n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
4	real NTO	perfect He	12.3	18	2	0.1	126.1	24.3	15.0	16.2	19.0	15.0	22.3	14.8
								2.08	n.a.	2.05	n.a.	n.a.	2.08	n.a.
5	real NTO	perfect He	12.3	18	2	0.1	114.2	14.3	14.6	15.4	17.4	20.1	19.6	20.1
								2.046	2.046	2.043	2.040	2.072	2.071	2.072
6	real NTO	perfect He	12.3	18	2	0.1	114.3	16.5	34.0	14.3	15.5	16.7	16.5	16.8
								1.4311	1.43097	2.06338	2.062	2.1	2.093	2.093
7	real NTO	perfect He	12.3	18	2	0.1	114.7	13.4	13.5	13.8	14.7	15.5	15.3	15.5
								2.085	2.078	2.085	2.081	2.108	2.107	2.110
8	real NTO	no fluid	12.3	18	2	0.1	0.47	66.0	66.4	68.2	212.7	302.9	116.0	132.6
								2.005	2.005	2.007	2.001	2.065	2.008	2.065

Table 4: Initial conditions and simulation results for priming cases in PIA Ox branch

Initial conditions and simulation results are listed in Table 4. Simulation in the remaining cases 1 to 7 has been performed with none condensable gases helium. On the one hand calculation time has been reduced noticeable, and on other hand the pressure peak level and time of maximal pressure has been predicted more accurate.

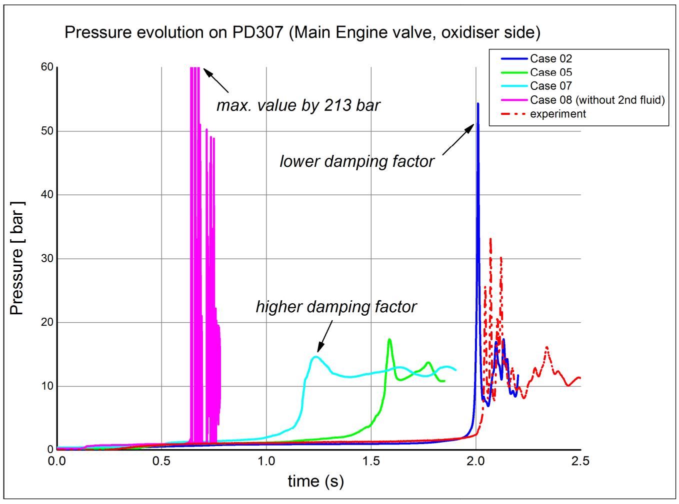

Figure 8: Comparison of simulation results with experiment by priming on sensor PD307

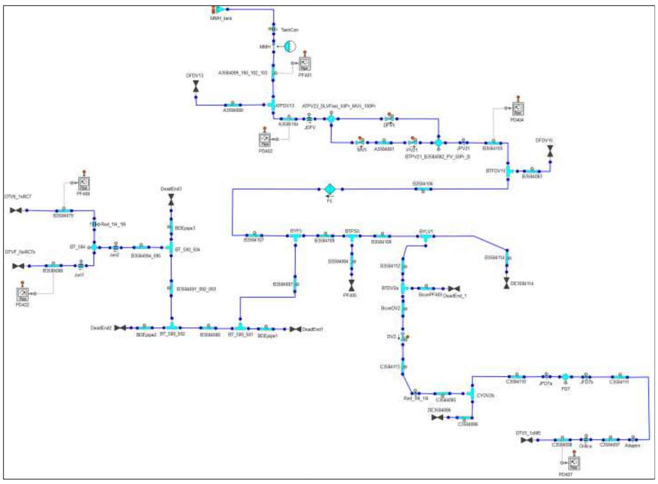

Figure 9: EcosimPro model of PIA fuel test setup

Initial assumptions and simulation results listed in table Table 5. Total six cases have been performed for MMH test setup. All simulation cases have been run with helium as second fluid.

Physical properties of MMH used in ESSPSS libraries seems to be analogical to NTO properties not sufficient for simulation of priming process as it was discussed above. This fact did simulation also slow and in some cases unstable.

case	FLUID 1 (propellant)	FLUID 2 (pressurant)	P tank	T tank	opening time	open time	sim time	Pressure sensor PF401	F5	PD402	PD404	PD422	PF405	PF408
[-]	[-]	[-]	[bar]	[°C]	[ms]	at [s]	[hr]	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec	[bar] at sec
1	real MMH	perfect He	12	20	2	0.1	n.a.	66.5	68.4	66.4	68.7	-	-	-
								0.406	0.405	0.406	0.405	-	-	-
2	real MMH	perfect He	12	20	2	0.1	n.a.	77.1	89.0	80.8	88.2	144.0	89.0	219.5
								0.797	0.797	0.797	0.797	0.794	0.797	0.792
3	real MMH	perfect He	12	20	2	0.1	n.a.	69.6	82.1	73.2	81.2	131.6	85.6	134.6
								0.800	0.799	0.799	0.799	0.795	0.799	0.795
4	real MMH	perfect He	12	20	2	0.1	31.5	66.1	78.6	69.5	77.6	126.6	81.5	128.7
								0.802	0.801	0.801	0.801	0.797	0.800	0.797
5	real MMH	perfect He	12	20	2	0.1	23.3	59.9	71.5	62.8	70.3	115.9	74.9	115.9
								0.803	0.802	0.802	0.802	0.798	0.802	0.798
6	real MMH	perfect He	12	20	2	0.1	23.6	54.2	64.4	56.6	63.2	107.0	68.2	106.7
								0.805	0.804	0.805	0.804	0.800	0.804	0.800

Table 5: Initial conditions and simulation results for priming cases in PIA Fu branch

There was one experimental case available only during working on the priming analysis. Table 6 show the measured pressure peaks. Simulation results are presented also in the table below.

		Experiment [bar]	Simulation pressure peaks [bar]					
Sensor	PFM Equivalent	mean	1	2	3	4	5	6
PD402	PIA Inlet	47.61	66.4	80.8	73.2	69.5	62.8	56.6
PD404	Pyro-Valve	42.89	68.7	88.2	81.2	77.6	70.3	63.2
PD405	Filter	43.98	n.a.	89.0	85.6	81.5	74.9	68.2
PD406	Main Engine Latch Valve	46.78	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PD407	Main Engine	0.00	0.0	0.0	0.0	0.0	0.0	0.0
PD408	RCT	139.21	n.a.	148**	134.6	128.7	115.9	106.7
PD420	FDV	43.91	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PD421	RCT branch inlet	108.52	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PD422	"5 RCTs"	109.82	n.a.	144.0	131.6	126.6	115.9	107.0

Table 6: Measured and calculated pressure peak during priming on oxidizer side

CORRELATION BY USING DAMPING FACTOR

A damping factor has been developed for better correlation of simulation results with experiment.

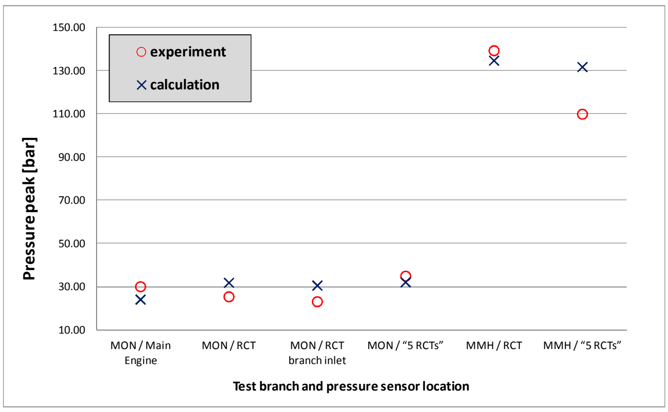

Figure 10: Experiment and simulation data with optimally damping factor

The damping factor is rising in simulation results from case 1 (min. value) to case 6 (max. value) for MMH. The same rise is observed from case 1 to case 7 for MON. The damping factor is based on the physical effect that small amounts of pressurant are dissolved in liquid propellant being stored in tanks. During pressure decrease by priming, helium is resolved and creates bubbles. The bubbles will be transported mixed with liquid and gaseous propellant as foam to the feed line ends. Then this mix will be compressed and helium bubbles will damp the priming shock. The damping factor adjusts this damping effect.

On the basis of performed calculations, an optimal value of a damping factor has been determined when simulation results are best correlated with experiment data. This damping factor is unique and in all investigated cases for the Exomars EVM system equal. Figure 10 presents the measured shock level and calculated values with an optimal damping factor at several positions in the feed system.

The results show that simulation results performed with optimal damping factor achieve very good correlation with experiment.

Since the found damping factor is unique for the investigated feed system, a tool was created to allow the peak pressures prediction of future similar feeds systems with good accuracy.

CONCLUSION

This paper describes analyses results for priming tests performed on simple test setups and on the Engineering Validation Model developed for the ExoMars program. Priming is a complex multi-phase phenomena that occurs in satellite or spacecraft propulsion systems. Analysis with EcosimPro on simple test setups has shown good correlation with test results found in literature for water and ethanol, but quite big deviations for propellants.

The accuracy of priming shock prediction could be improved with introduction of damping factors during EVM tests validation. We were able to adjust the simulation approach by introduction of a damping factor and to achieve quite high precision in priming shock level prediction. This approach has been used in flight model simulations and can be used in other programs.

It is believed that improvement of propellant properties data contained in EcosimPro and extension of calculation approach with consideration of pressurants solubility in propellant can increase the accuracy of priming results and also calculation stability.

ACKNOWLEDGMENT

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