FLUIDIC TESTING OF AN IN-ORBIT MONOPROPELLANT REFUELLING SYSTEM

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ABSTRACT:

In the new age of space, a sustainable space industry is key to continue with a responsible inhabitance of the available orbits. To do that, one of the available approaches is to extend the current satellites' time with additional propellant using an external refueling satellite. To allow this capability, a new sort of refueling design is needed – with the aim of being simple, off the shelf and cheap whilst being reliable.

In order to develop such a system, a simplified fluidic breadboard is setup at Thales Alenia Space UK (TASUK) as part of the UK Space Agency (UKSA) Active Debris Removal (ADR) Phase B study, to simulate an in-orbit monopropellant refuelling system using water as a simulant. The primary goal of this setup is to demonstrate concept of operations for the transfer of propellant from a visiting tanker to the COSMIC (Cleaning Outer Space Mission through Innovative Capture) spacecraft via delta pressure whilst using existing off the shelf building blocks. The test plan aims to characterize the system behavior for nominal and extreme cases, for critical operation scenarios and calibrate analysis tools to be able to characterize and optimize the design along the project development.

The critical operations considered in the scope of this test campaign are the repetitive priming phenomenon, sudden valve shutdown due to power loss scenarios causing water hammer, and propellant transfer.

The analysis tool used to calibrate the model is EcosimPro with European Space Propulsion System Simulation (ESPSS) tool kit – a widely used tool in the space industry, co-developed with ESA.

Results from the overall test campaign will help assess and establish operating conditions for safe operation of the flight subsystem and to validate overall refuelling concept of operations, and as can be seen in the paper the analysis showed a good agreement between the model and the test results.

1. INTRODUCTION

1.1. COSMIC ADR

One of the biggest global challenges facing the space sector is orbital congestion and space debris, this problem will only increase as more satellites are launched into orbit.

The Astroscale COSMIC spacecraft is competing for the national ADR mission led by the UK Space Agency and will harness Astroscale's rendezvous and proximity operation (RPO) and robotic debris capture capabilities.

The mission aim is to capture 2 UK-registered, inactive satellites and bring them down to a low orbital altitude where they will safely and swiftly de-orbit.

In-space refuelling of the spacecraft will enhance the capabilities of COSMIC. Refuelling enables COSMIC to capture and de-orbit additional clients and will reduce the need for further spacecraft to be built and launched.

Therefore we can reduce the environmental impact from multiple launches and improve the economic return.

To de-risk the refuelling process, TASUK successfully conducted breadboard testing of the fluidic design to understand the steady-state and dynamic pressure response; this campaign successfully contributed to our system PDR status.

1.2. Refuelling Subsystem

The refuelling subsystem comprises of the COSMIC propulsion subsystem and a potential tanker propulsion subsystem, henceforth referred to as the visiting vehicle (VV). Both the COSMIC and VV subsystems use hydrazine as propellant. The aim is to transfer propellant between the VV and COSMIC subsystems through a differential pressure (DP) between the two tanks. Sufficient DP between the two tanks would initiate propellant transfer from the VV tank to the COSMIC tank, thus refuelling it.

2. TEST OBJECTIVES

All tests that are part of this test campaign are conducted using the industry standard of water simulant for Hydrazine (N_2H_4). The primary goals of the test campaign were as follows:

- Support risk reduction of hydrazine refuelling operations.
- Calibrate numerical models of the refuelling subsystem (using EcosimPro, MATLAB).
- Inform, demonstrate and characterise propellant transfer operations.
- Demonstrate and characterise critical transient operations for priming and refuelling pause.
- Transfer at least the required propellant amount from VV tank to COSMIC tank.

3. TEST METHODOLOGY

The test matrix is composed of a set of test cases that can be grouped together by test type as shown in Table 1.

Table 1: COSMIC Test Matrix

Test Type	VV Tank Pressure	COSMIC Tank Pressure
Priming	Nominal	N/A
Refuelling Pause	Nominal	Nominal
	Nominal	Worse case
CONOPS	Nominal	Nominal
	Nominal	Worse case

Since the refuelling operation is achieved via a differential pressure between the VV and COSMIC tanks, it is the main variable parameter for refuelling pause and CONOPS tests. The variation in differential pressure is achieved by setting the COSMIC tank pressure at a Nominal value or worse case value depending on the test case.

Typical distributions of pressure transducers, flow meters and scales are shown in more detail in a reduced schematic in Figure 1.

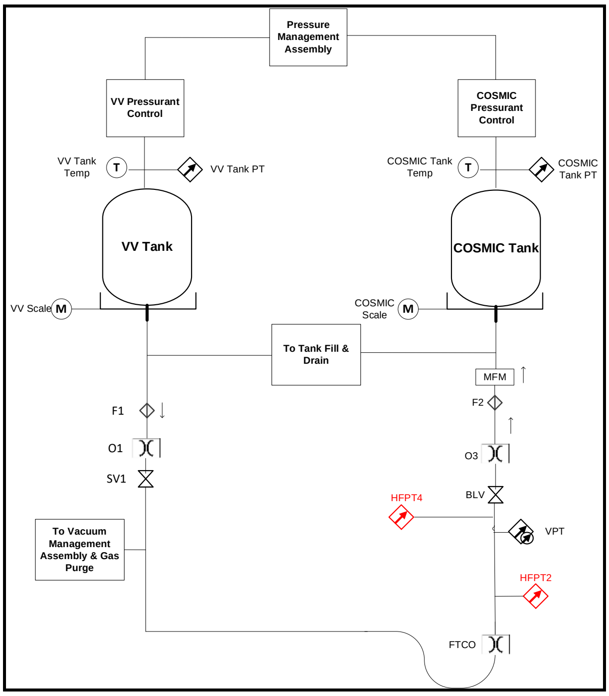

Figure 1: Test Schematic

3.1. Priming Characterisation Tests

Priming tests are performed by setting up a positive delta pressure between the VV and tubing section of the refuelling subsystem, which is typically set up to be in vacuum condition. The priming is then executed by opening the final solenoid valve on the VV into the vacuumed section up to the closed representative ball latch valve (BLV). Priming tests are conducted at a nominal tanker pressure with representative ullage fill fractions and using one representative orifice for the fluidic transfer coupling (FTCO) in the priming flow path. The pressure is then recorded at locations where peak pressure will occur using high frequency pressure transducers (HFPTs).

3.1.1. Success Criteria

Success criteria for priming characterisation tests are as follows:

- Pressure peaks recorded at relevant HFPTs are repeatable as per the uncertainties of the HFPTs.
- Observed pressure peaks are within the operating safety limits of the system.
- Pressure waves caused by priming dampen to up to ±5% of steady state pressure within 10 seconds.

3.1.2. Repeatability Requirement

The initial vacuum condition in the fluidic setup can have a significant impact on the magnitude of the priming pressure peaks. It is therefore crucial to establish a criteria to demonstrate repeatability of the measured peak pressures across test runs.
Repeatability is demonstrated by measuring the

delta peak pressure ΔP_{peak} for each priming test run. The definition of the delta peak pressure is as given in Eq. 1

$$\Delta P_{peak} = P_{peak} - P_{settled} \qquad \text{Eq. 1}$$

where, P_{peak} is the first pressure peak and $P_{settled}$ is the final pressure measured by the relevant HFPT. The pressure value, $P_{settled}$, is measured at a pre-defined time interval from the first pressure peak. Since ΔP_{peak} is calculated from two pressure measurements, the uncertainty of ΔP_{peak} is twice the uncertainty measurement ($\mathrm{HFPT_{UM}}$) of the applicable pressure sensor. Based on this, the repeatability requirement is as summarised in Eq. 2.

$$\Delta P_{peak,run\,1} - \Delta P_{peak,run\,2} \leq \pm 2 \times HFPT_{UM} \qquad \text{Eq. 2}$$

Two test runs are considered repeatable if the condition in Eq. 2 is met.

3.2. Refuelling Pause Characterisation

The main objective of the refuelling pause characterisation tests is to demonstrate transient behaviour of the refuelling system due to a sudden pause in refuelling operation. These tests are executed by closing the representative BLV during fluidic transfer between the VV & COSMIC. The BLV is opened and, after a pre-set wait time to reach a “steady flow”, the BLV is closed to observe the effects on the recorded pressure peaks of a sudden valve shut-off during the high flow rate when the delta pressure is largest between the two tanks.

A pre-defined sequence of operations was executed by the data acquisition software in order to automate the valve closure. This helped to ensure repeatability of test conditions across multiple test runs.

3.2.1. Success Criteria

Success criteria for priming characterisation tests are as follows:

- Pressure peaks recorded at relevant HFPTs are repeatable as per the uncertainties of the HFPTs.
- Observed pressure peaks are within the operating safety limits of the system.
- Pressure waves caused by priming dampen to up to ±5% of steady state pressure within 10 seconds.

3.2.2. Repeatability Requirement

Since the refuelling pause test success also depends on the observed pressure peaks using HFPTs, the repeatability requirement for the refuelling pause is the same priming characterisation, as is the defined in Eq. 2, Section 3.1.2.

3.3. Demonstration of CONOPS

The purpose of these tests is to demonstrate the concept of operations (CONOPS) of the propellant transfer between the VV and COSMIC. These tests include pressurising the COSMIC tank and VV tank to worse case or nominal differential pressure and allowing propellant transfer between them until pressures are equalised between the tanks. Each test is a slight variation of the stages described, with different delta pressures between the tanks while maintaining the same fill fraction.

3.3.1. Success Criteria

The success criteria for the demonstration of CONOPs was to successfully transfer simulant from the VV tank to the COSMIC tank at nominal and worse case DP, and to capture the evolution of pressure and mass measurements in both tanks during the transfer cycles.

4. TEST SETUP

The breadboard model (BBM) was built and tests were executed in the TASUK Fluidic Lab located at the Harwell Campus. The COSMIC and VV breadboards are mostly composed of commercial off-the-shelf (COTS) products, chosen to be as representative to flight system equipment as possible. In the few cases where representative COTS equipment could not be sourced, custom orifices were procured to model this missing equipment.

Figure 2 below shows a block diagram of the test setup.

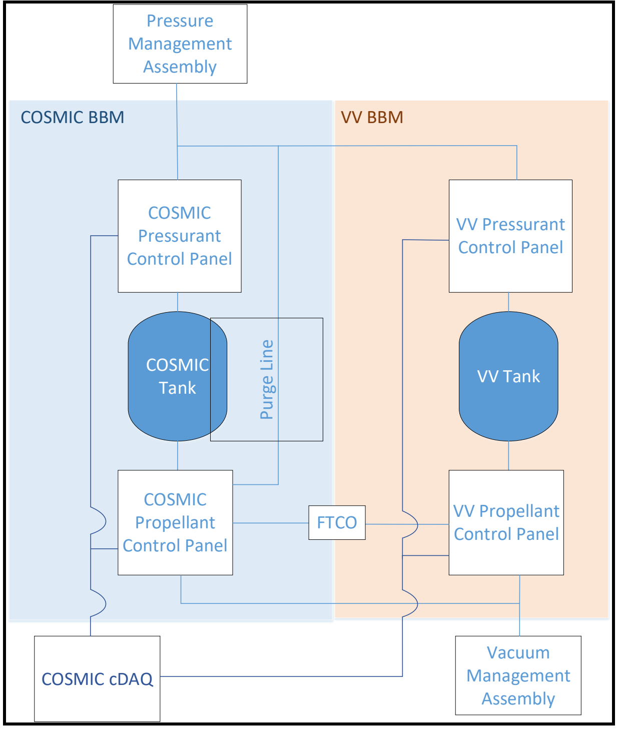

Figure 2: COSMIC test setup block diagram

The setup allowed for demonstration of operations, primarily propellant transfer from the VV tank to the

COSMIC tank. The direction of propellant transfer and system priming only occurred from the VV tank to the COSMIC tank.

Water bladder tanks were used to represent the VV and COSMIC diaphragm tanks. These tanks were placed on weighing scales, shown in Figure 3 to measure the mass of simulant in the tank during a propellant transfer test. A mass flow meter was installed on the fluidic panels to measure flowrate between tanks, shown in Figure 4 on the top left panel.

Figure 3: COSMIC Overall Setup

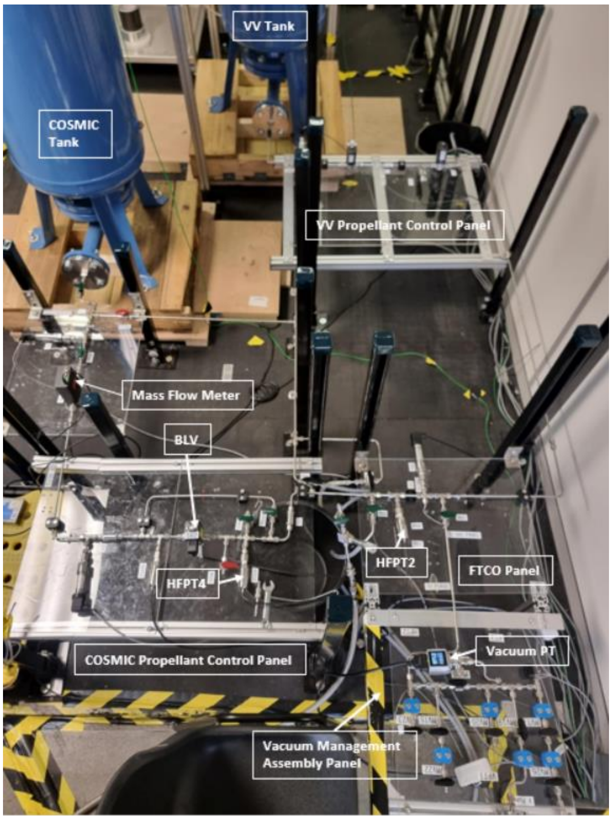

Figure 4: COSMIC Tank (left) and VV Tank (right) with Mass Flow Meter directly below COSMIC Tank outlet (left)

Pressure transducers (PTs) were distributed in key locations throughout the breadboard to determine steady state and slow changing pressures. High frequency pressure transducers (HFPTs) were placed in areas of interest for pressure peaks. In addition to these, a vacuum pressure transducer was connected to the tubing between the two tanks to allow verification of vacuum following operation of the vacuum management assembly. This facilitated the execution of priming tests.

5. ANALYSIS SETUP

5.1. EcosimPro

EcosimPro (ESP), developed in collaboration with ESA, is a continuous-discrete simulation tool for modelling physical processes such as fluidic analysis (transients, pressure drops, performance etc). This is a standard tool used across TASUK for various projects using modelling principles and parameters which have been developed and verified using data obtained on previous test campaigns. An EcosimPro model representative of the fluidic breadboard setup was created and used to analyse priming & fluidic transfer test cases.

5.2. MATLAB Model

The MATLAB model is a TASUK developed numerical model used to quickly assess various CONOPS for refuelling scenarios. The model provides a final steady state estimation of the mass transfer between the tanks and the final tank pressures, which is then compared to the EcosimPro Model and the test data.

6. RESULTS

6.1. Priming Tests

The propellant lines between the VV and COSMIC in flight will be in a vacuum condition prior to the refuelling operation. In order to begin refuelling those lines must be hard-filled with liquid; this is done through vacuum pumping on the ground, and through venting in flight. The final valve within the VV (SV1, Figure 5) is opened allowing liquid to flow into the vacuum-evacuated lines up to the BLV in COSMIC causing a highly dynamic, water hammer event. This water hammer is caused by the rapid change in velocity and fluid momentum of the liquid at the dead end, causing a potentially damaging spike in pressure. Therefore priming tests are a critical component of the campaign to validate that pressure peaks caused by water hammer are kept within acceptable pressure limits of the system to avoid structural failure.

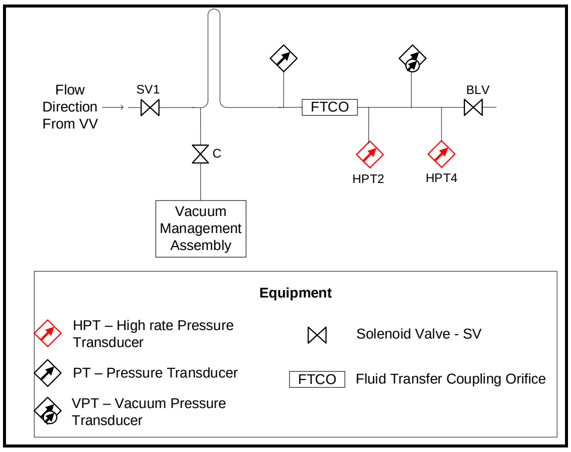

Figure 5: Example equipment setup for priming

All priming tests in the campaign are conducted with a tubing line at a representative vacuum pressure. To achieve this, a vacuum is drawn from near the line inlet. The pressure is measured by a piezo vacuum transducer at the opposite end of the line. This ensures the worst case (highest pressure) initial condition is measured. This is critical as the liquid entering the line can mix with the residual gas, forming a vapour cushion which effects the evolution of the first pressure peak [1].

All tests were performed twice to ensure repeatability & vacuum levels prior to test were verified. Extensive testing was performed before the priming test series to ensure no water vapour remained in the lines and the system's reverse leak rate was acceptable.

Figure 6 and Figure 7, show the priming pressure peaks for both test runs at locations where the highest pressure peaks were to be expected. The results meet the repeatability criteria described in Section 3.1.2 and the priming pressure peaks are well below the range of hydrazine detonation pressure.

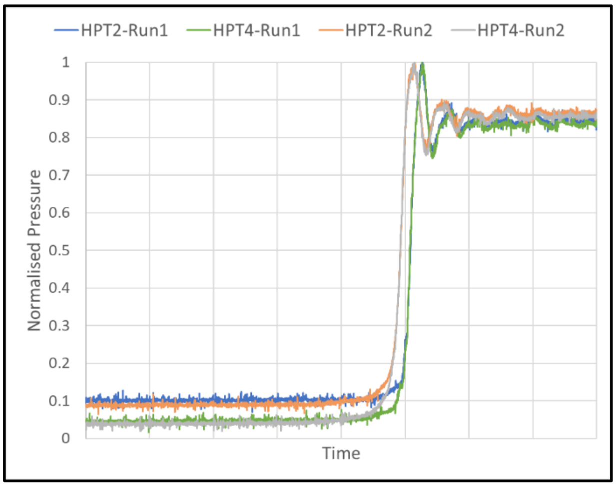

Figure 6: Priming steady state & transient

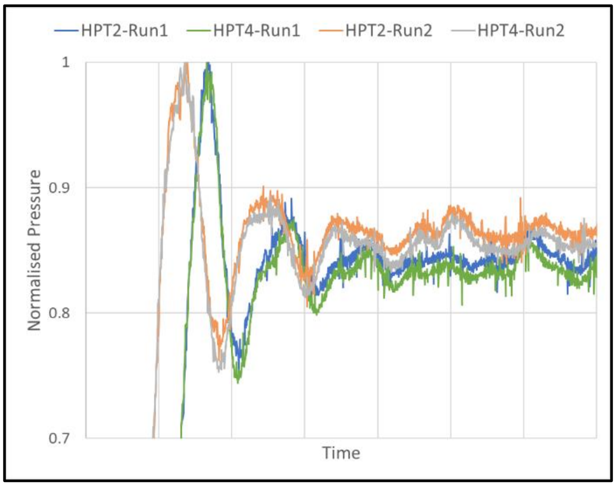

Figure 7: Priming pressure peak

Figure 8 and Figure 9 show the comparison of both priming test runs with the ESP model, which is represented by the dashed lines.

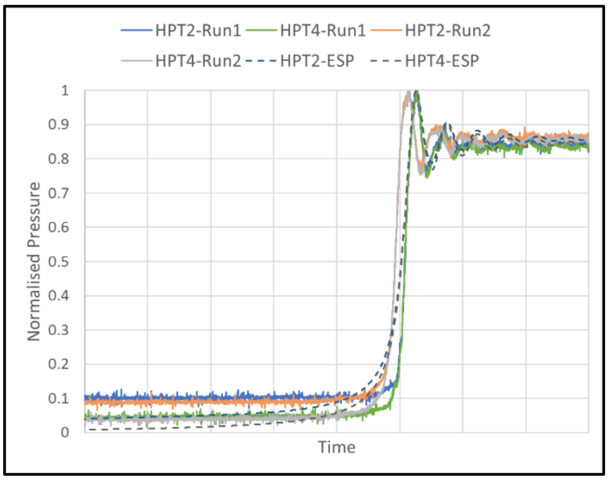

Figure 8: Priming pressure peak

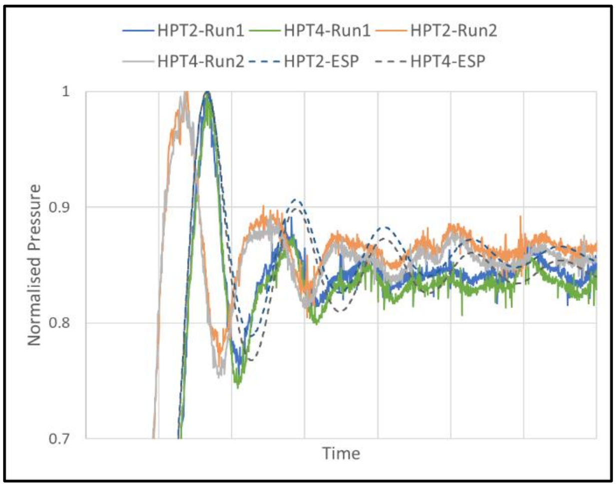

Figure 9: Priming pressure peak

The ESP model shows good agreement with the priming test data, with representative pressure rise, pressure peak, timing & damping effects in both HFPT locations.

6.2. Refuelling Pause

Once the system is primed and the final VV valve is open, steady pressure-differential fed refuelling begins. However, it is important to be able to stop the refuelling process by closing the valves. This could be necessary due to an emergency or nominal operations for a pause or end of transfer. The closing of a fast-acting valve causes a water hammer transient which can damage components if the peak is too high.

To simulate a refuelling pause or stop, a flow of water in the test setup is established via a pressure differential between the VV and COSMIC tanks. Tests were performed for two cases, a nominal and worse case differential pressure (DP).

Figure 10 and Figure 11 show the pressure peak due to waterhammer caused when the representative BLV is closed, for nominal and worse case DP. Each pressure differential test case was run twice to ensure repeatability. Both pressure differentials show similar peak pressure, pressure rise & damping behaviour.

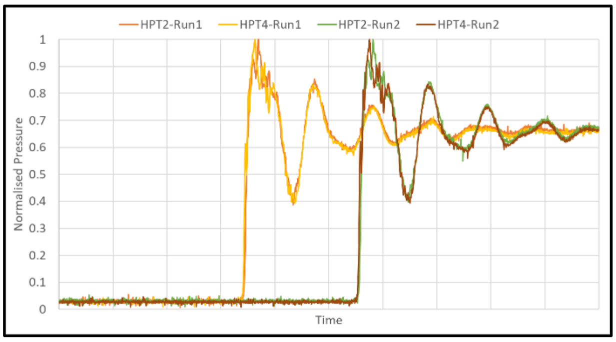

Figure 10: Pressure peak at worse case DP

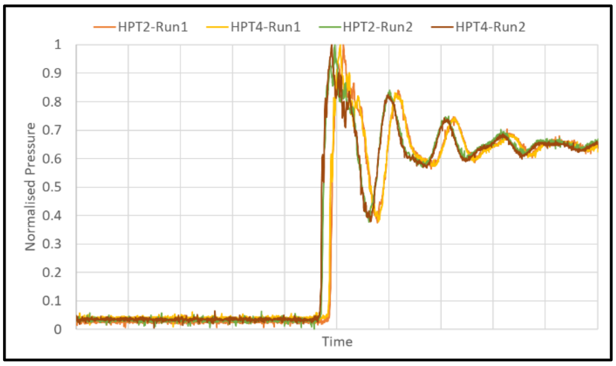

Figure 11: Pressure peak at nominal DP

An offset can be seen between Run 1 and Run 2 in Figure 10 and Figure 11 which can be attributed to software limitations which can cause a slight offset when sending the voltage off signal to the solenoid valve. This offset, however, does not affect the magnitude of the observed pressure peaks, pressure rise and pressure wave damping behavior. The test results are therefore compliant with the repeatability requirement mentioned in 3.2.2.

6.3. Propellant Transfer

This test represents the baseline refuelling operation for COSMIC. Firstly, the VV & COSMIC tanks are pressurised by the Pressure Management Assembly. After the final stage of priming has been completed, the BLV in the COSMIC Propellant Control Panel is opened, initiating simulant transfer. As the transfer progresses, the static pressure of the VV tank reduces & the COSMIC tank pressure increases until pressure equalisation.

The test is a single blowdown operation with no repressurisation of the VV tank. Static pressures and mass flow rate were measured throughout the system at a sampling frequency of 1 Hz for the duration of the demonstration.

Due to the higher accuracy of the mass flow meters compared to the weighing scales, the recorded flow rate data was integrated over time to obtain the propellant transfer curve.

The demonstration on CONOPS test case was executed at both nominal and worse case DP. Each DP test case was run twice to ensure repeatability.

6.3.1. Nominal DP

Figure 12 shows pressure equalisation between the VV and COSMIC tank for test data which is compared against the data obtained from ESP for the nominal DP case. Both test runs are repeatable and show good agreement with ESP results.

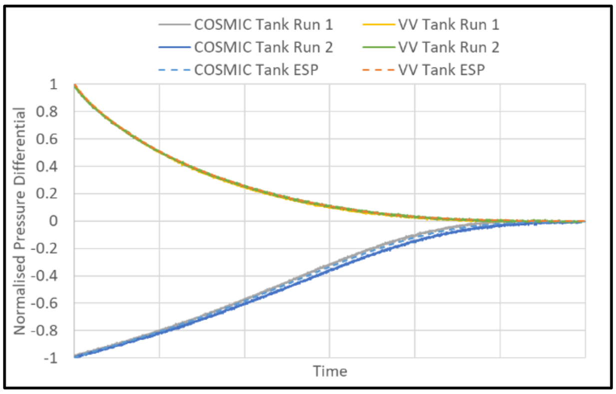

Figure 12: Pressure equalisation between tanks, test data vs EcosimPro (ESP) at nominal DP

Figure 13 shows the evolution of the mass transferred between the VV and COSMIC tanks.

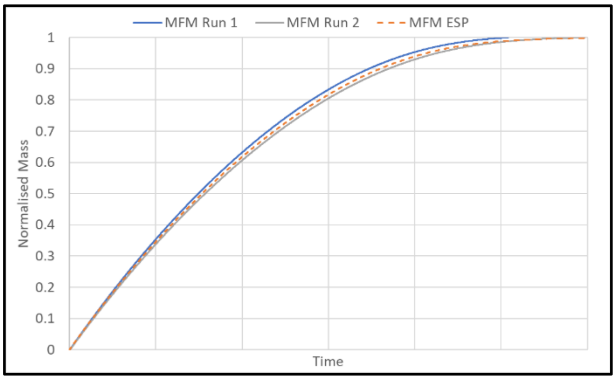

Figure 13: Propellant transfer between tanks, test data vs EcosimPro (ESP) at nominal DP

Both test runs are repeatable and show good agreement with ESP results.

Figure 14 shows the evolution of the mass flow rate over the duration of the propellant transfer cycle. As expected, when the BLV is opened to initiate simulant transfer, the mass flow meter registers a peak in the mass flow rate. This peak is within safe operational limits of the system. The mass flow rate reduces over time as simulant is transferred from the VV tank to the COSMIC tank and the pressure equalizes between the two tanks.

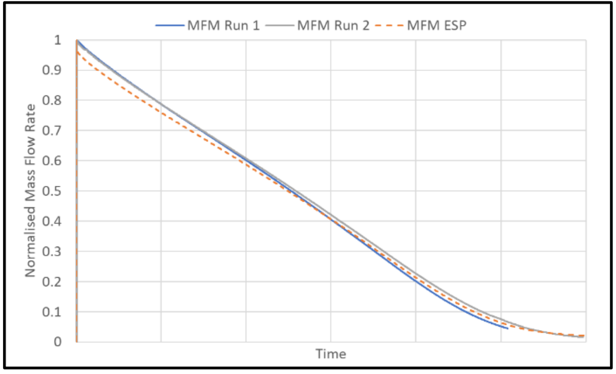

Figure 14: Normalised mass flow rate between tanks, test data vs EcosimPro (ESP) at nominal DP

Both test runs show repeatable test results and show good agreement with ESP results.

6.3.2. Worse Case DP

Figure 15 shows pressure equalisation between the VV and COSMIC tank for test data which is compared against the data obtained from ESP for the worse DP case. Both test runs are repeatable and show good agreement with ESP results.

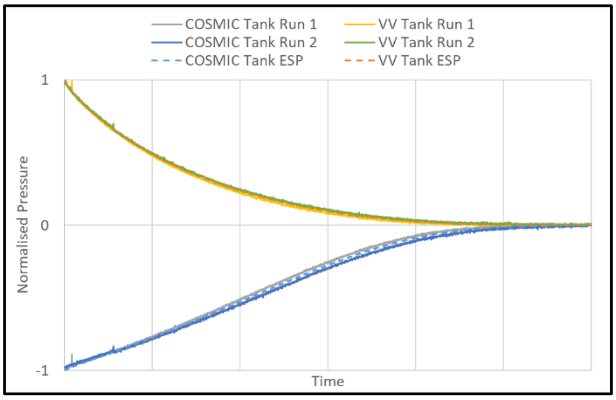

Figure 15: Pressure equalization between tanks, test data vs EcosimPro (ESP) at worse case DP

Figure 16 shows the evolution of the mass transferred between the VV and COSMIC tanks.

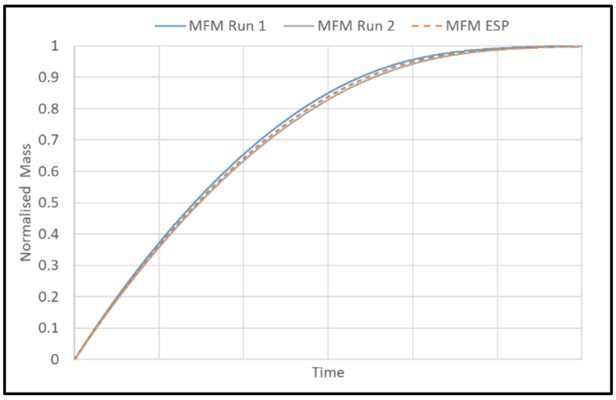

Figure 16: Propellant transfer between tanks, test data vs EcosimPro (ESP) at worse case DP

Both test runs are repeatable and show good agreement with ESP results.
Figure 17 shows the evolution of the mass flow rate over the duration of the propellant transfer cycle. Similar to the nominal DP case, when the BLV is opened to initiate simulant transfer, the mass flow meter registers a peak in the mass flow rate. This peak is within safe operational limits of the system. The mass flow rate reduces over time as simulant is transferred from the VV tank to the COSMIC tank and the pressure equalizes between the two tanks.

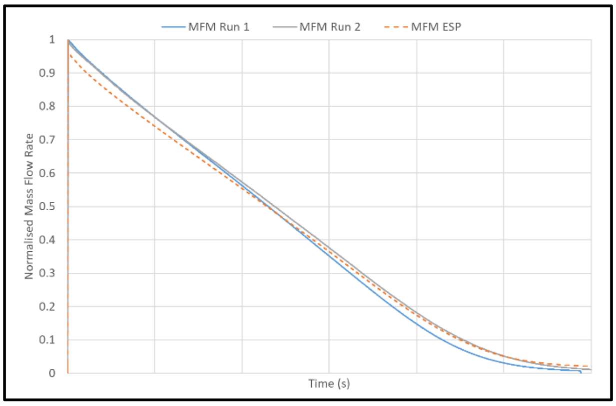

Figure 17: Normalised mass flow rate between tanks, test data vs EcosimPro (ESP) at worse case DP

Both test runs are repeatable and show good agreement with ESP results.

7. ANALYSIS SUMMARY

The analysis summary in Table 2 shows the percentage error between the analysis methods, ESP & MATLAB, with respect to the averaged test data.

The analysis shows good agreement with the test data and provides confidence in TASUK analysis methodology for priming and fluidic transfer.

Table 2: Percentage error of MATLAB & Ecosim Pro to test data

Differential Pressure	Data	Equalisation Pressure (%)	MFM Mass Transfer (%)
Nominal	Matlab	-1.60	N/A
	ESP	0.11	2.11
Worst case	Matlab	-1.36	N/A
	ESP	0.50	3.20

8. CONCLUSION

The campaign successfully demonstrated the objectives of the COSMIC fluidic test campaign. All test results were repeatable and comparable to the analysis. Additionally, the pressure equalisation and mass flow rate evolution trends observed show good agreement with similar tests that were previously conducted at TASUK, which are summarised in [2].

The primary objectives achieved are as given below:

- Demonstrate and characterise concept of propellant transfer operations:
    - The test campaign successfully demonstrated propellant transfer from the VV tank to the COSMIC tank.
    - Total propellant transferred for the high and low case DP cases exceeded the required propellant to be transferred.
- Demonstrate and characterise critical priming operations:
    - The test campaign successfully demonstrated repetitive priming phenomenon with repeatable pressure peaks.
    - Priming pressure peaks were found to be within the safety limits required for a hydrazine monopropellant system.
- Demonstrate and characterise transient operations:
    - The test campaign successfully demonstrated refuelling pause scenario caused due to sudden valve shutdown.
    - Pressure peaks observed due to water hammer were found to be within the safety limits required for a hydrazine monopropellant system.
- Calibrate numerical models for COSMIC analysis (via EcosimPro & MATLAB). Numerical models for the subsystem and propellant transfer are shown to be accurate and can be applied in preparation for future refuelling missions. All test results showed good agreement with the simulation model results with low error.

The test and simulation results can be used to inform COSMIC refuelling analysis, systems design, budgets and feed into the future VV design. The results can also be used for predicting system performance with a monopropellant, instead of a simulant, which will help drive the design of the COSMIC refuelling subsystem as the project matures.

9. REFERENCES

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