DEVELOPMENT TESTING AND ANALYSIS OF THE INTEGRATED GATEWAY-ESPRIT BIPROPELLANT REFUELLING SYSTEM

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ABSTRACT:

The Gateway will be humanity's first space station orbiting the Moon completed by NASA in partnership with ESA and other US and international partners. The Gateway will provide critical support to sustainable human exploration on the moon through the Artemis program. To enable the Lunar Gateway to complete its mission, on orbit refuelling is essential. The ESPRIT Refuelling Module (ERM) will provide the capability to transfer propellants, MMH and MON-3, through the Habitation and Logistics Outpost (HALO) to the Power and Propulsion Element (PPE). The transfer of these propellants carries known risks and hazards. These hazards include overpressure of the propellant lines during priming sequences between modules and during refuelling pause operations. To support the early system development and to mitigate these risks, a collaborative test program between NASA, ESA and Thales Alenia Space was completed at the Thales Alenia Space test facility in Harwell, UK. This test program integrated fluidic breadboards of the ERM, HALO and PPE modules. The objectives of the test program were to demonstrate and characterise critical performance and transient operations, inform refuelling concept of operations and to calibrate and validate numerical models of the refuelling subsystem in EcosimPro. To support the completion of this final objective a detailed model of the integrated breadboard was developed in EcosimPro and key steady-state and transient test cases were simulated. As an industry first, a National Institute of Standards and Technology (NIST) database correlation for Hydrofluoroether (HFE-7000) was used as a mixed oxides of nitrogen (MON-3) simulant with EcosimPro and European Space Propulsion System Simulation (ESPSS) libraries to result in a more accurate analysis for transient phenomenon such as priming. The test and simulation data showed good agreement validating the model for further system analysis as the ERM design progresses.

1. INTRODUCTION

1.1. Introduction to the Gateway

The Gateway will be an orbiting lunar space station providing support to human return to the surface of the Moon. It is a critical component to NASA's Artemis program.

The Gateway will initially consist of two elements to be launched as part of Artemis III. These elements will be the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). Together these are referred to as the Co-Manifested Vehicle (CMV). The PPE features a high performance, 60-kilowatt xenon-based solar electric propulsion system and a higher-thrust bipropellant chemical propulsion system. This propulsion package will provide attitude control and orbital transfer capability for the Gateway. HALO will provide the initial crew quarters for visiting astronauts and will have several docking ports for visiting vehicles and future modules [12].

The first two modules of Gateway will then be joined by the European modules, ESPRIT-RM (European System Providing Infrastructure and Telecommunications – Refueller Module) and I-HAB (International Habitation Module). Each of these modules will provide additional living space for astronauts. In addition, ESPRIT-RM will provide the functionality to refuel the Gateway propulsion systems.

A rendering of Gateway including elements from multiple international partners is shown in Figure 1. PPE can be seen on the far left connected to HALO, while the ESPRIT-RM is located on the northern leftmost radial port.

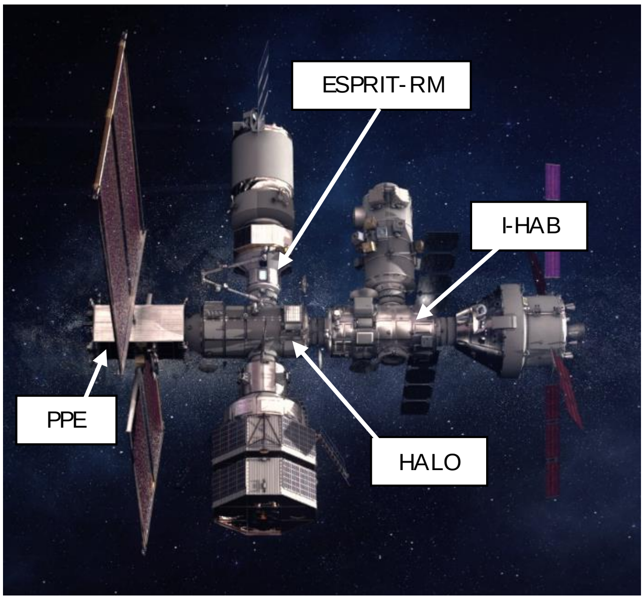

Figure 1: A rendering of Gateway, including elements from international partners (Credit: NASA/Alberto Bertolin)

1.2. Gateway Refuelling

Each of the bipropellant and xenon propulsion systems of Gateway will be refuelled over the course of the Gateway life time. ESPRIT-RM will provide this refuelling infrastructure including the propellant and the pressurant required to complete the refuelling activities. Xenon, monomethylhydrazine (MMH), and mixed oxides of nitrogen (MON-3) will be transferred from ESPRIT-RM through HALO to PPE. The refuelling path for MMH and MON-3 is shown in *Figure 2*.

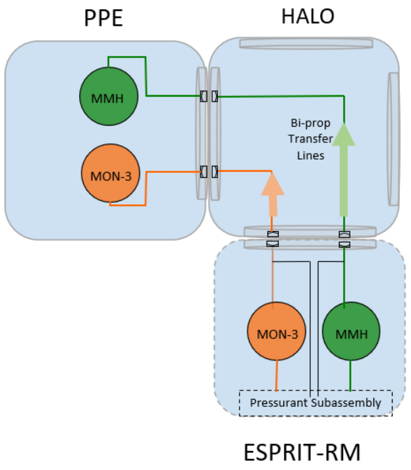

Figure 2: Simplified diagram of bipropellant transfer path

1.3. ESPRIT Module

The ESPRIT-RM is one of the two modules that are contributed by Europe to the Gateway. The module will be docked to the HALO module, led by NASA, via an International Berthing and Docking Mechanism (IBDM). This includes fluidic coupling to facilitate transfer of propellant between the Gateway modules.

ESPRIT-RM provides four major functionalities:

- Bipropellant and Xenon refuelling capabilities;
    - Propellant Refuelling from the ESPRIT-RM to the PPE to enable extension of the space station lifetime and excursions capabilities;
    - Additionally, the Bipropellant Transfer Subsystem (BTS) has the capability to transfer propellant from a Visiting Vehicle (VV) cargo ship to the PPE propellant tanks;
- Pressurized access between HALO and Visiting Vehicles for Crew and Cargo passage;
- External viewing capabilities of Moon, Earth and Gateway surroundings;
- Internal pressurised logistics loading at launch.

ESPRIT-RM is led by ESA, with Thales Alenia Space in France as the prime contractor.

1.4. ESPRIT Bipropellant Transfer Subsystem

Thales Alenia Space in the UK is responsible for the design and development of the Bipropellant Transfer Subsystem (BTS) on the ESPRIT-RM module. This subsystem will provide the bipropellant refuelling functionality to refuel the Reaction Control System on PPE.

The BTS is capable of transferring propellant through an active gas-pressurised blowdown transfer. The BTS is capable of adjusting the mass flow rate of propellant transfer between the BTS, VV and PPE by altering the flow paths between the modules. The BTS also provides the following supporting functions:

- In-orbit leak checking of refuelling fluidic networks and refuelling couplings via helium pressure decay;
- Priming pressure surge control;
- Propellant purging of tubing networks to ensure minimised propellant hazards when crew is present;
- Propellant tank venting to control source pressure.

A simplified schematic of the architecture is presented in *Figure* .

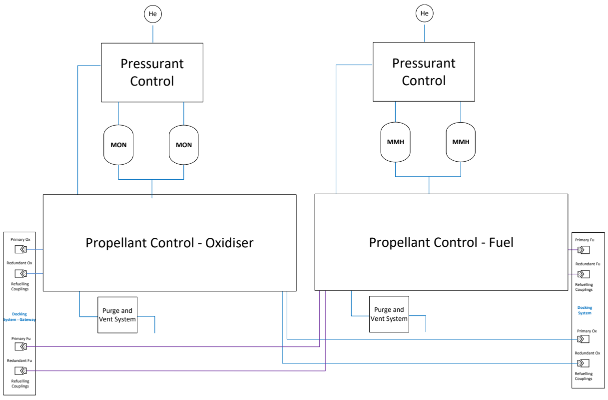

Figure 3: BTS simplified fluidic architecture

The baseline architecture of the BTS utilises many qualified propulsion equipment, with developments needed for some equipment to adjust to the new refuelling application. The major development on equipment level is the propellant and pressurant flow control valves, due to the potential for backflow and changes of standard interfaces.

The development plan of the BTS contains three main stages at subsystem level.

The first stage includes a simulant based breadboard model to validate analysis and de-risk the subsystem's major operations. This breadboard model also allows the investigation of worst case interface conditions coming from other connected systems which are undefined, such as the conceptual visiting vehicle refuelling architecture. This breadboard model consists of commercial off the shelf items were carefully selected to closely match the key performance characteristics of flight models, including pressure drop and valve response time. Tubing lengths were matched to current preliminary designs but the exact tubing geometry was not matched flight model design. This simulant based breadboard model is the focus of this paper.

The second stage of the subsystem development is a propellant development model which will act as a functional simulator of the subsystem to support the verification and validation of the subsystem. This model will include full engineering models of equipments driving the performance of the subsystem. This model will also match both the tubing lengths and geometry of the flight model design.

The third subsystem development activity is conducted in the frame of the flight model acceptance tests to ensure proper functionality and build quality. This will include pressure testing and valve functional tests but no transfer of simulant or propellant. The acceptance tests will support the successful delivery of the module.

2. ANALYSIS AND TEST OBJECTIVES

As part of the first development phase, the ERM-1 breadboard test campaign had the following primary objectives:

- Support de-risking of refuelling operations;
- Calibrate numerical models for BTS transient analysis (via EcosimPro);
- Contribute useful results to inform Gateway refuelling analysis;
- Demonstrate and characterise propellant transfer operations;
- Demonstrate and characterise critical transient operations.

3. TEST SETUP

The breadboard was designed to facilitate a demonstration of Gateway refuelling from the ESPRIT-RM tanks to the PPE tanks, from the Visiting Vehicle (VV) tanks to ESPRIT-RM tanks and direct refuelling from the VV tanks to PPE tanks. These refuelling scenarios were representative of the flight system. To reduce complexity, only a single leg of the system was simulated. However, redundant solenoid valves were employed where appropriate to create a better representation of the expected flow path through the primary leg.

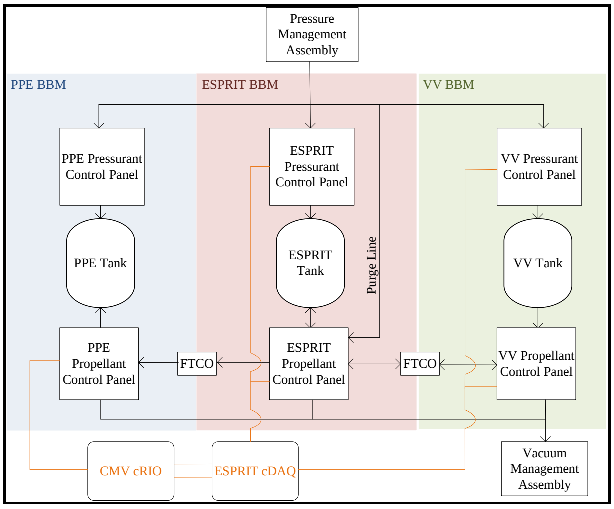

Figure 4: ERM-1 joint test setup block diagram

Breadboards for ESPRIT-RM and VV were designed and produced by Thales Alenia Space in the UK as per the block diagram shown in Figure 4. The PPE and HALO Co-Manifest Vehicle (CMV) breadboard was under the responsibility of NASA and transferred from the Johnson Space Centre after initial testing to be integrated with the ESPRIT-RM and VV simulant breadboard. [1]

Across the breadboards, commercial off the shelf equipments were predominantly used; however all items were selected to be as representative to flight equipment as practicable. Subscale tanks were used to enable a lower volume of simulant in the system (and hence a reduced operational time). Representative fill fractions and tank pressures were used across the test cases. The volume of simulant in the tanks was measured with scales and monitoring the change in mass, coupled with a mass flow meter at the ESPRIT tank outlet to measure mass flow rate between the tanks. Pictures of the assembled breadboard are shown in *Figure 5* and *Figure 6*.

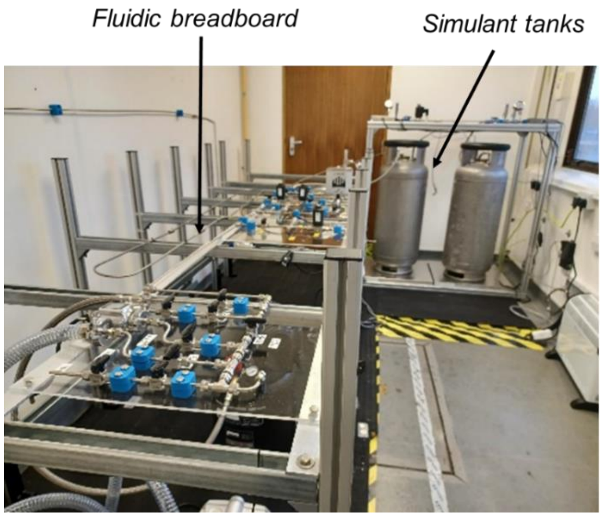

Figure 5: Fluidic network and tanks configuration

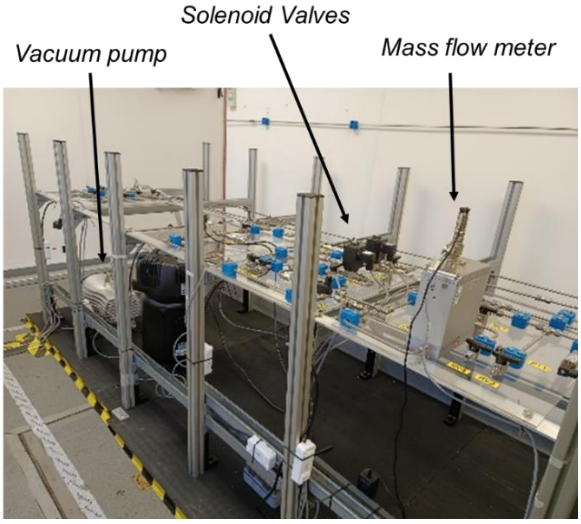

Figure 6: ESPRIT and VV BBM Fluidic panels with Flow Meter

Keller (PA33X and PAA33X) and RS (797-5030 and 797-4961) pressure transducers were used across the breadboard to measure steady state and slow-change pressures. In areas where transient peak pressures due to priming would occur, Kistler (4260A) high frequency transducers were used. This is shown in *Figure 7.*

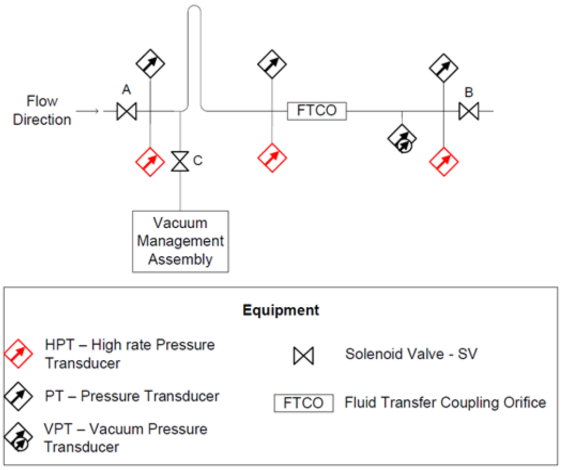

Figure 7: Example setup of pressure transducers in an area of interest with regard to priming peaks.

Figure 8 shows the arrangement of high and low frequency pressure transducers around a valve with potential pressure peaks due to refuelling pause. The high frequency pressure transducer upstream of the valve was used to capture the peak pressure following the valve closure in a refuelling pause. The high frequency pressure transducer downstream of the valve was used to capture the pressure oscillation following the valve closure in a refuelling pause. Temperature sensors were also employed across the breadboard.

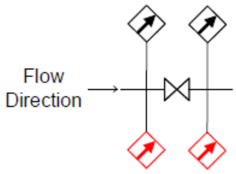

Figure 8: Example setup of pressure transducers for refuelling pause tests.

4. TEST METHODOLOGY

Three types of tests were conducted as part of the test campaign to meet the test objectives: priming characterisation, refuelling pause characterisation, and pressure drop characterisation. Tests were conducted using water as a simulant for MMH, and HFE-7100 as a simulant for MON-3. These simulants are industry standard for MMH and MON-3 respectively and their use can be justified by the similarities in fluidic properties as shown in Table 1. HFE-7000 was used in the analysis cases modelling HFE-7100 test cases.

Table 1: Comparison of fluidic properties for propellants and simulants

Fluid	Ref. Temp (°C)	Density (kg/m^3)	Dynamic Viscosity (kg/(m.s)	Vapour Pressure (bar)
DI water [4]	25	995	8.949e-4	0.0316
MMH [5]	20	880	7.75e-4	0.05
HFE-7100 [6][7]	25	1520	5.74e-4	0.269
HFE-7000 [8]	25	1400	4.48e-4	0.65
MON-3 [9]	20	1446	3.34e-4	0.95 (at 25 °C)

4.1. Transient Characterisation Tests

It is important to characterise transient phenomena such as priming and waterhammer to prevent pressure peaks in the propellant lines that could exceed the safety limits of the system. Priming and refuelling pause tests are grouped under transient characterisation tests to characterise critical transient operations.

Pressure peaks caused due to transients are captured using high frequency pressure transducers, which were sampled at a frequency of 10 kHz.

4.1.1. Priming Characterisation Tests

Prior to beginning refuelling operations, the tubing sections between the ESPRIT and PPE tanks have to be primed with propellant. This constitutes introducing propellant flow into tubing sections that are at a vacuum condition. Priming into a tubing section that is set at a vacuum condition causes pressure peaks due to a rapid change in fluid momentum. It is therefore essential to characterise pressure peaks caused due to priming to ensure operation within the safety limits of the system.

From preliminary testing conducted at Johnson Space Centre [1], it was made clear that the small differences in the vacuum condition had a large impact on the peak pressures during priming. This is because the liquid entering the line can mix with the residual gas, forming a vapour cushion which effects the evolution of the first pressure peak [2]. As such, the vacuum condition was carefully prepared in each test case, heating the lines and drawing vacuum for up to six hours. Directly prior to each priming stage, a vacuum decay test was performed to ensure an appropriate initial condition. This vacuum decay test was conducted for 10 seconds and required measured vacuum pressure to not exceed 0.13 mbar. Longer vacuum decay tests were also conducted to ensure the evacuated line was also adequately dry. The pressure was measured by a piezo vacuum transducer at the opposite end of the line to the vacuum pump. This ensures the worst case (highest pressure) initial condition is measured.

Priming characterisation tests are performed using water and HFE-7100. The test matrix capturing the priming tests for different start conditions, defined in terms of source pressure, is as shown in Table 2.

Table 2: Priming Characterisation Test Matrix

Test Case	Simulant	Source Pressure
TRA-1a	Water, HFE-7100	Nominal
TRA-2	Water	High
TRA-3	Water, HFE-7100	Low

Simulations using an analytical model are run for TRA-1a and TRA-3 using simulant properties for water and HFE-7000, and the simulation results are compared with the test results.

4.1.2. Refuelling Pause Characterisation Tests

During refuelling operations, a sudden pause in refuelling due to valve closure can cause pressure peaks due to the waterhammer effect. It is therefore essential to characterise this phenomena to ensure that the expected pressure peaks do not exceed the safe operating limits of the system.

4.2. Pressure Drop Characterisation Tests

The refuelling path comprises of different flow restricting elements such as valves and orifices which affect the flow rate for a pressure differential between the tanks. These characterisation tests allow characterisation of multiple flow paths for different start conditions measured by the various pressure differential values such that the mass flow rate can be interpolated for any delta pressure across different flow paths. Unlike transient tests, steady pressure measurements are recorded with a standard pressure transducers sampling at 1 Hz.

5. ANALYSIS SETUP

EcosimPro is a continuous-discrete one-dimensional simulation tool used for the modelling of physical processes [10]. Consisting of a package of libraries based on the EcosimPro simulation environment, the European Space Propulsion System Simulation (ESPSS) toolkit provides an extensive set of individual components that are used to model complete in-space propulsion system. This enables the performance of the system and any fluidic phenomena ensuing from its operation to be analysed. ESPSS allows for the modelling of the behaviour of two-phase two-fluid mixtures in both steady-state and transient cases [11]. Flows that can be simulated include depressurisation of liquid fronts into evacuated feed lines, waterhammer effects, and the flows of fluid through orifice and filter elements.

The simulant test breadboard, consisting of representations of ERM, CMV and VV, was replicated in the EcosimPro environment utilising components provided in the ESPSS libraries. As a balance between representativeness and computational cost, the pressurising gaseous helium, or nitrogen where applicable, was modelled as a perfect gas. For simulant, real fluid properties were considered through the use of ESPSS fluid property files. Notably, a literature search yields that this is an industry-first use of National Institute of Standards and Technology (NIST) correlations for HFE properties. HFE-7000 properties were used to simulate the HFE-7100 used in the test, as there was a good agreement for density and viscosity. Although there was some difference in the vapour pressure between the two fluids, this discrepancy was deemed acceptable as there was a marked improvement from water and simplified fluids as these assume zero vapour pressure.

Both the transient and characterisation tests performed were replicated in the simulation environment for analysis. Critically, dissolution of the pressurant in the simulant was assumed negligible at timescales on which the test was conducted. Moreover, heat transfer and temperature fluctuations were neglected at these timescales. Pressurant flow was assumed unrestricted to maintain constant tank pressures. For the transient cases, an initial condition of the ESPRIT-RM tank pressure was defined alongside an initially-evacuated downstream feed line. Pressures through the feed system were measured against time from valve opening. Transient valve opening characteristics were replicated for this analysis. Two-phase correlations for wall internal friction coefficients were used. For the pressure drop characterisation cases, a differential pressure boundary condition between the ESPRIT-RM and PPE tanks was set and the mass flow rate measured. The pressure drop characterisation cases assumed single phase liquid.
For this study, EcosimPro v5.4.19 and ESPSS v3.1.0 were used.

6. RESULTS

All test and simulation results are presented as normalised pressures. The pressures for transient cases are normalised by the initial tank pressure. For the pressure drop characterisation, the differential pressure is normalised by the maximum operational differential pressure.

6.1. Priming Characterisation

Figure 9 shows the normalised peak pressures for the different test and analysis cases for water as mentioned in *Table 2*. It can be seen that the normalised peak pressure increases as the source tank pressure increases. From further analysis of the test data, it can be shown that the peak pressure is linear with respect to source tank pressure. This is because a larger source tank pressure enables higher momentum of the liquid column before contacting the ends of the primed volume. The test data for the high (TRA-2) and nominal (TRA-1a) source pressure cases shows good agreement with the analysis data for the frequency and the damping response.

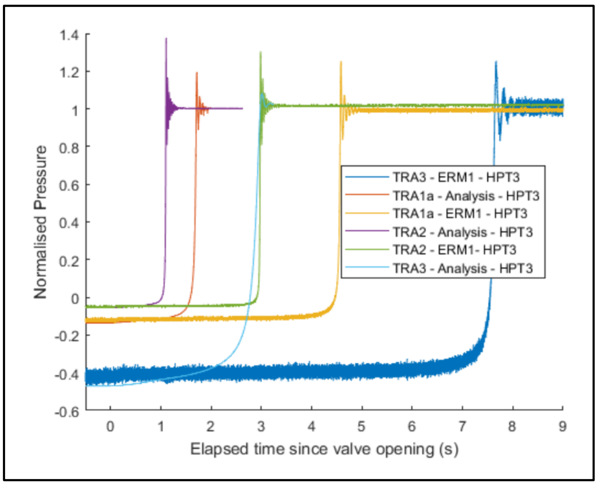

Figure 9: Comparison of Water Priming Test and Analysis Results

Simulation results matched the peak pressure magnitude to a higher accuracy for the high initial tank pressure case than for the nominal case. For water priming conducted at low initial tank pressure (TRA-3), the simulation closely matches the frequency of the experimental response. However, the simulation under-predicts the peak pressure, and the response decays faster than that measured experimentally.

Figure 10 compares the test results for HFE-7100 with analysis results for HFE-7000. As expected, the data shows similar trends to the test and analysis done with water.

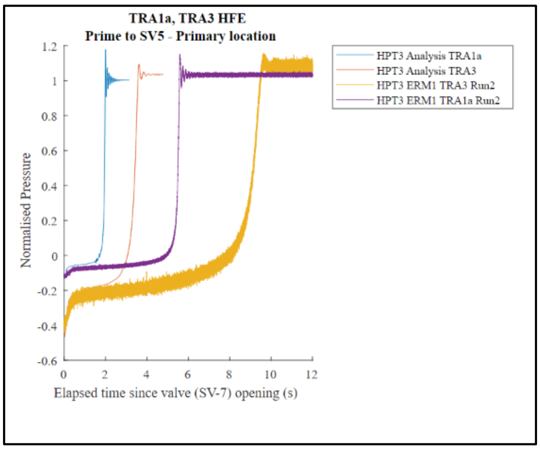

Figure 10: Comparison of HFE-7100 priming tests results with HFE-7000 simulation results

For HFE priming conducted with a nominal initial tank pressure (TRA-1a), the analysis matches the magnitude and damping measured experimentally, but shows a higher frequency. For HFE priming conducted with a low initial tank pressure (TRA-3), the simulation matches the experimental frequency and decay of the pressure wave, but under-predicts the magnitude of the response.

It can be seen in Figure 9 and Figure 10 that the duration between valve opening and peak pressure is shorter for simulation than experiment. This is in line with previous similar analysis completed with EcosimPro [3].

6.2. Refuelling Pause Characterisation

Refuelling pause tests were conducted by closing the isolation valve between ESPRIT-RM and PPE after a stable flow rate was established between the two tanks. The sudden pause in flow causes pressure transients due to waterhammer both upstream and downstream of the isolation valve, which were recorded during tests with water. The sudden closure of the isolation valve was also simulated with EcosimPro using water properties by establishing similar start conditions as the tests. Figure 11 compares the peak pressure recorded upstream of the isolation valve during testing and as obtained by analysis for water.

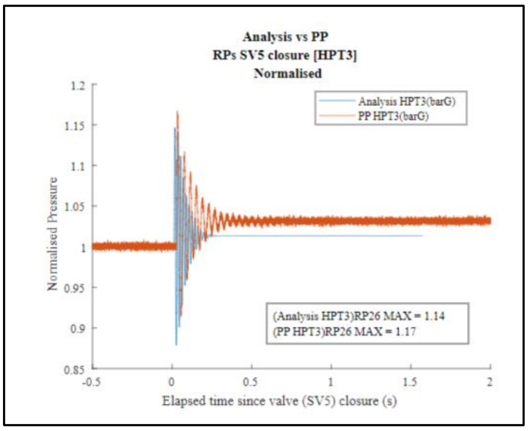

Figure 11: Comparison of Test and analysis pressure peaks recorded upstream of sudden valve closure

Upstream of the valve, the analysis results match well with experiment in terms of magnitude of the response. However, the frequency and damping factor measured during the test are slightly higher than predicted by analysis.

Figure 12 below compares the peak pressure recorded downstream of the isolation valve during testing and as obtained by analysis for water.

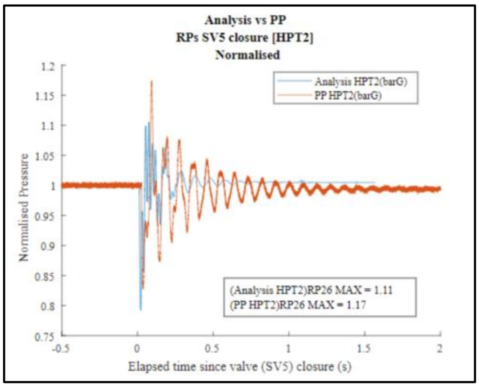

Figure 12: Comparison of Test and analysis pressure peaks recorded downstream of sudden valve closure

Downstream of the valve, the analysis results under-predict the peak pressures and show a faster decay than what is observed experimentally. There is good agreement on the frequencies observed in the response. A secondary mode in the frequency response was measured experimentally. This was also captured in the analysis.

6.3. Pressure Drop Characterisation

Pressure drop characterisation tests and simulations are done for two different flow paths: CHA-1a and CHA-3. Across each flow path, the differential pressure between the ESPRIT-RM and PPE tanks is varied in order to obtain the mass flow rate versus differential pressure trends for both flow paths. Normalised differential pressures between 0 and 1, represents the expected operating pressure range. Normalised differential pressures above 1 are considered beyond normal operating pressures244558*.

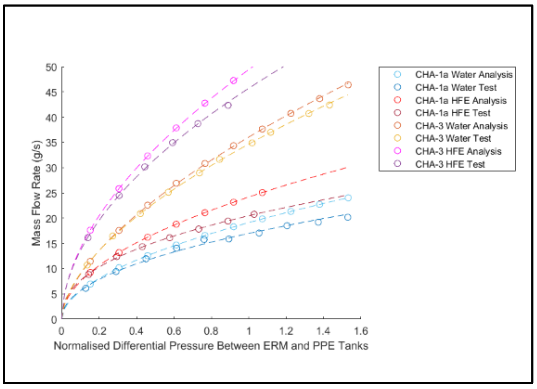

Figure 13: Comparison of test and analysis results for pressure drop characterisation for different flow paths at varying differential pressures

From Figure 13 it can be seen that there are varying levels of agreement between experimental and analytical characteristics of mass flow rate and differential pressure. Generally, the agreement is strong at lower differential pressures and better for water than for HFE. The high flow path characterisation (CHA-3) analysis conducted with both water and HFE simulants matches the experiment well over the entire range of data. The discrepancy between the simulation and test for the

CHA-1a nominal flow path characterisation is initially small but increases with higher differential pressures.

7. CONCLUSION

The simulant breadboarding campaign successfully completed its key objectives, supporting the de-risking of the key refuelling operations outlined in this paper. The data was successfully used to calibrate the numerical fluidic models for transient and steady state performance analysis. The data collected informed several design optimisations that were implemented in the preliminary design phase of the ESPRIT-RM program.

This analysis successfully demonstrated good correlation between HFE-7100 test cases and analysis cases using the HFE-7000 property file.

8. FUTURE WORK

Early planning of the propellant development model for the second stage of the BTS subsystem level development is already underway. Several lessons learned from the simulant campaign have been taken forward. The propellant development model will be used to refine the simulation models of the subsystem and reduce discrepancy between test and simulation results.

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