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ARES II – Axial Retention Experiment for Propellant Management Devices Sponges

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ABSTRACT

In this paper, the authors present the scientific results of the ARES II experiment, launched on the REXUS 23 sounding rocket in March 2019 [1].

The ARES II experiment was conceived to investigate the behaviour of liquids in "sponge" type PMDs (Propellant Management Device). These devices (Figure 7), composed of radial panels tapering towards their centre to collect liquid at a certain desired position by capillarity, are used in the space propulsion community to guarantee the delivery of bubble-free propellant to the liquid propulsion engines when high reliability is needed. Sponge devices rely on surface tensions to control and deliver fluid to a desired location in microgravity environments. The capillary force is generally negligible with respect to hydrostatic one in gravitational environments. On the contrary in microgravity, where hydrostatic forces related to accelerations are much smaller than on earth, the surface tensions cannot be neglected any more.

The behaviour of liquids in sponges subjected to accelerations perpendicular to their axis was investigated in the past by several authors [2][3][4]. The purpose of the ARES II experiment instead is to investigate the behaviour of liquids in sponges subjected to accelerations acting on the axis of the sponge itself.

From the beginning of the 1960s surface tension PMDs were known and used in space vehicles. Though, limited general public documentation is available on this subject. In particular, about the liquid behaviour in sponges under axial acceleration, no information is available in the public domain. The purpose of this experiment is to fill this void by putting sponges in microgravity and acquiring images of the fluid distribution.

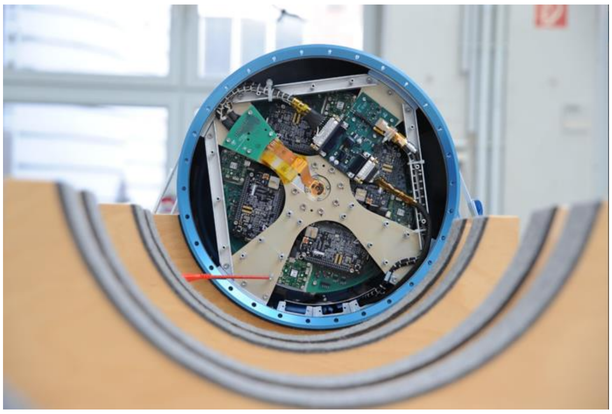

Figure 1: ARES-II on bench test in ZARM, Bremen

1. Design Overview

Like in CAESAR [2], the experimental setup is designed to carry four identical sponges, each one filled at a different level. The experimental fill ratios tested are 37%, 50%, 75%, 100%.

The sponges are placed in a centrifuge that activated once the experiment reached microgravity to apply axial acceleration to the samples.

The sponges were subjected to increasing axial accelerations and the liquid behaviour was recorded.

The experimental results are here after compared with numerical simulations.

1.1. Numerical predictions [5]

A series of preliminary CFD (Computational fluid dynamics) investigations were performed prior to designing the system to determine key experiment setup

parameters such as the sponges' dimensions and rotational speeds.
Like in the experimental investigations stated before, four fill ratios were simulated:
37%, 50%, 75% and 100%.
For each fill ratio, 6 acceleration steps, corresponding to the following bond numbers (Eq.1): 0, 0.90, 1.09, 1.24, 1.55 , 2.32 were applied.

As shown in Fig. 2, the CFD simulations were conducted on a 1/12th slice of the sponge, taking advantage of the axial symmetry of the device.
The simulation were performed with 1 million of tetrahedral meshing elements, with fine elements in the proximity of the sponge surface and coarser elements away from the sponge.

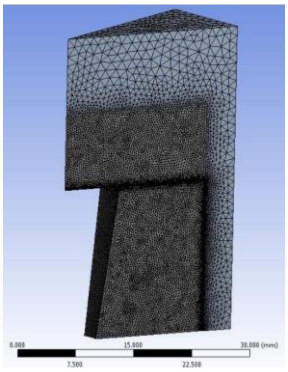

Fig. 2, Meshing of PMD sponge

Once the relevant phenomena identified by the CFD predictions, the hereafter stated bond number similarity was used to determine the experimental acceleration scaled to ARES PMDs size.

$$Bo = \frac{\rho a L^2}{\gamma} \qquad (1)$$

Where :

ρ : the density of the fluid, here 967 kg/m^3
a : the acceleration applied to the sample
L : characteristic length, here: D/2
γ : the surface tension of the fluid, here 0.02 N/m

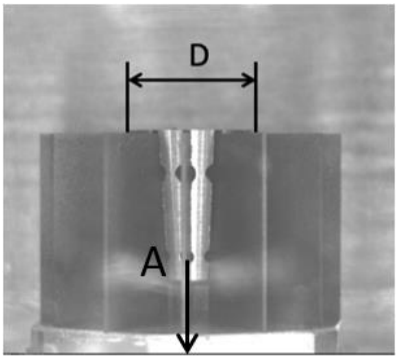

Figure 3, PMD sponge reference diameter (D) and acceleration direction (A)

1.2. Mechanical Design

The experimental setup was composed by a rotating plate with four test cells. On each test site, was inserted a sponge, with its axis directed toward the rotation axis. Four cameras, one for each test cell, were recording the liquid behavior. It observed the droplet coming out axially from the sponge.
The centrifuge system was designed to provide an axial acceleration to the sponges between 0 and 8m/s^2 corresponding to a bond range between 0 and 9.7.
The liquid was injected into the sponges from a pressure tank when the rocket reached microgravity.

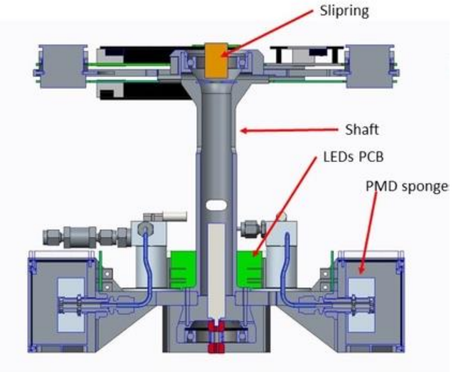

Figure 4, cut view at 0°

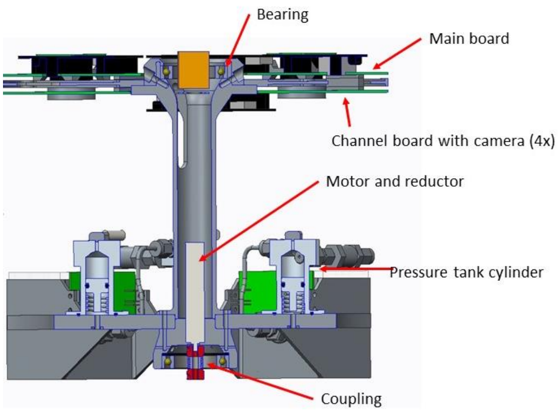

Figure 5, cut view at 45°

The experiment plates subassembly contained the test cells with the sponges. For each one, a pressured injection system, an acquisition board and an illumination system was integrated.

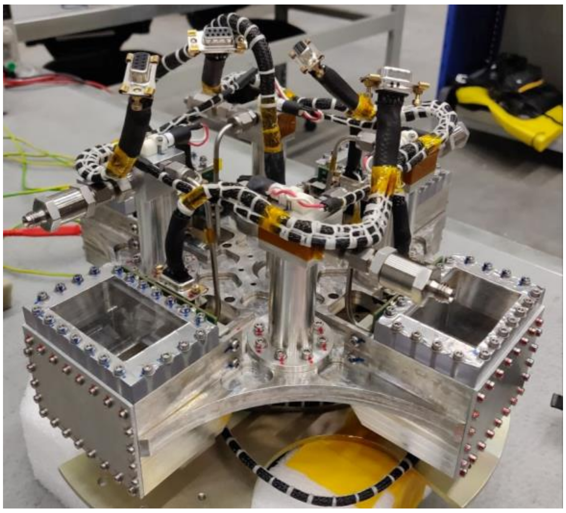

Figure 6, experiment plate with injection system and acceleration acquisition boards

The 25mm diameter sponges were machined in titanium by electro discharge milling process [6]. They contained 12 panels 0.36 mm thick and 15mm height. The conical core shape was 7mm diameter at its basis and 10mm at the top. The liquid was injected from the centre core of each sponge.

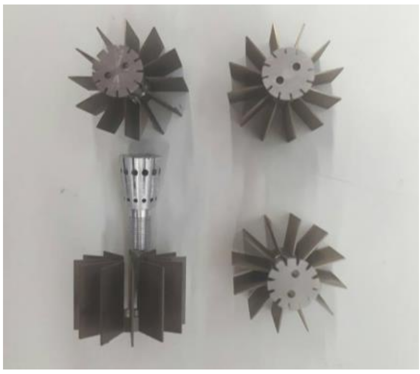

Figure 7, PMDs sponges tested

1.3. Electrical Design

The electronic design was composed of several electronic boards and components, like shown in Fig 8.

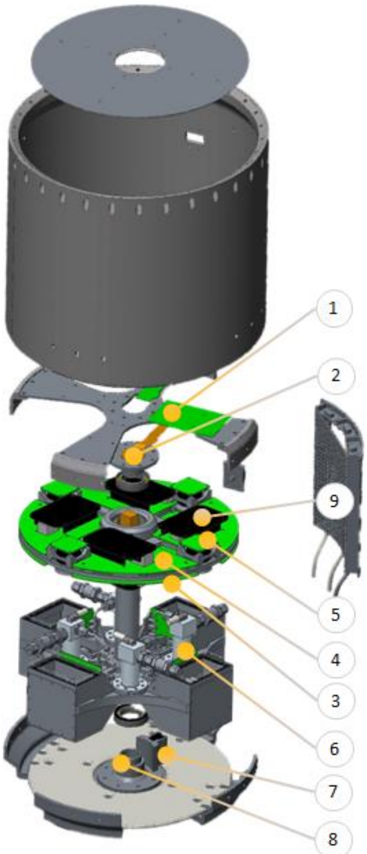

Figure 8: ARES-II Experiment exploded view

In reference to the Fig. 8.1 the topboard, interfaces with the RXSM module was equipped with sensors, such as accelerometer and temperature.
Fig. 8.2 The electrical bridge between the static and rotating part of the experiment was done with a slip-ring.
Fig. 8.3 The mainboard (beneath the plate) was receiving the RXSM signals (SOE, SODS, LO) and

communicating the experiment data to the ground station using the downlink from the RXSM module.
Fig 8.4. A total of 4 channelboards were acquiring and storing the camera footage Fig 8.5 from their respective test cell which each contains a PMD sponge. They were also gathering their onboard sensors data and the data from the oncellboard Fig 8.6. The acceleration and temperature measurement was implemented as close as possible to the test cell in order to acquire the most precise data from the 4 PMDs sponges.
Fig 8.7 A lock mechanism was retaining the experiment from moving from lift-off to the apogee of the rocket. The aim of mechanism was to avoid disturbing the dynamics of the rocket.
Fig. 8.8 A brushless motor associated with a closed loop control system was enabling the experiment to compensate the residual spin of the rocket by counter spinning the experiment. After a completion of residual spin compensation, the centrifuge is gently speedup to provide an axial acceleration to the PMDs sponges.
Fig 8.9 The design was based on the BeagleBone Black board, which is a known electronic development platform highly used in universities. It has been used for different projects and therefore we had software and hardware support to model our architecture around this device. The OS was built from scratch using a custom buildroot kernel, this was especially done to avoid carrying to unnecessary processes.

2. REXUS 23 Flight

The rocket REXUS 23 was launch from Esrange Space Center in Northern Sweden [1]. The launch was originally planned for March 2018 but was postponed due to failure on its sister rocket REXUS 24. The REXUS 23 was finally launched on March 2019 with a lift off at 09:50 local time and reached an apogee of 75km.

The experiment performed as normally, except for the loss of a channel at lift off, (Channel 0). The preliminary results showed that the experiment performed correctly and the injection and spinning procedure went without any noticeable issue. On re-entry the rocket did not open the parachute which resulted on a very hard landing of the payload on the cold ice of Sweden.

2.1. Post Flight Investigation

Subject to a non-nominal landing, a post flight analysis of the mechanical parts was carried out to evaluate the damages caused by the landing and to collect the SD cards where the data is stored.

Impacts on the experiment shields were clearly visible and nuts remained trapped where the absorbing foam was not shielded (Fig. 9)

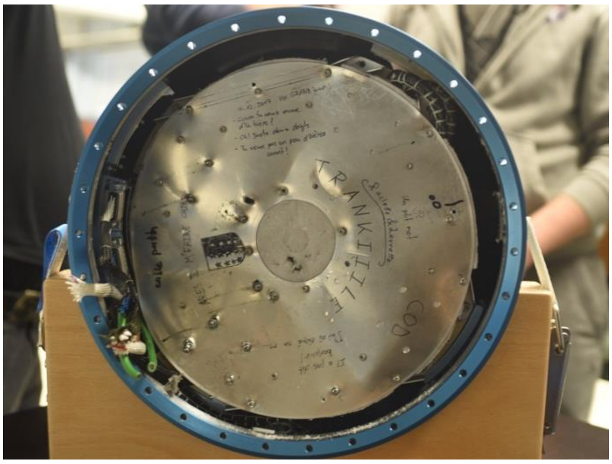

Figure 9: Upper experiment shield

Several pieces (mechanical, electronic) were moving freely on the bottom of the module. These parts were mostly parts from other experience which flow across the rocket on impact due to enormous force generated by the landing.

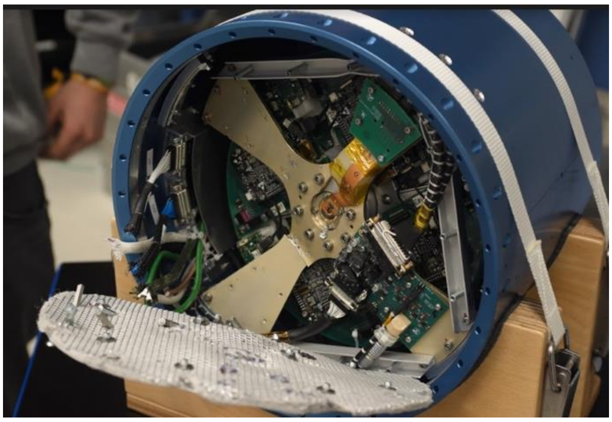

Figure 10: Experiment top view

The impacts seen on the shields of the experiment, were clearly visible on the upper bulkhead. An impact broke this last one, exactly on the SD Card holder of a BeagleBone Balck (Channel 2). The SD card was bent and the die was broken, the data could not be retrieved, so overall only two SD cards remained (channel 1 and 3).

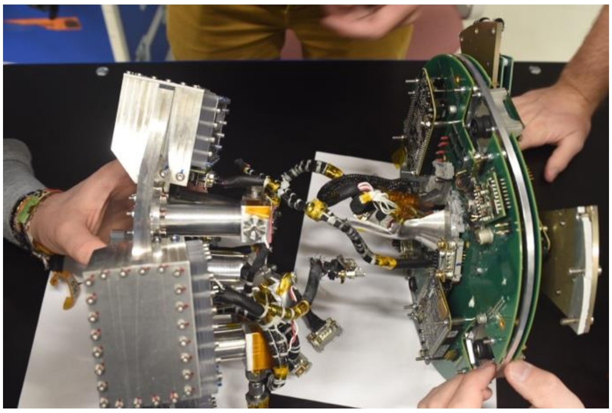

Figure 11: Experiment separated after landing impact

The experiment had encountered a lot of compression, the full experiment had shortened by compression by 1/3 its size. The mechanical axis deformed until fracture, shrinking the experiment.

Figure 12: Capacitor bank of motor drive impact

Several impacts are noticeable on the electronic board which have major component destruction, like the capacitor bank for the motor drive in Figure 12

In summary, the landing destroyed an SD card, but 2 out of 4 remained and data was retrieved. It makes sens now to investigate second storage to avoid this kind of unfortunate situation. The world is built on error and failure and we can only know better for the next time.

2.2. Flight results

Despite the hard landing, two test cells observations were usable.

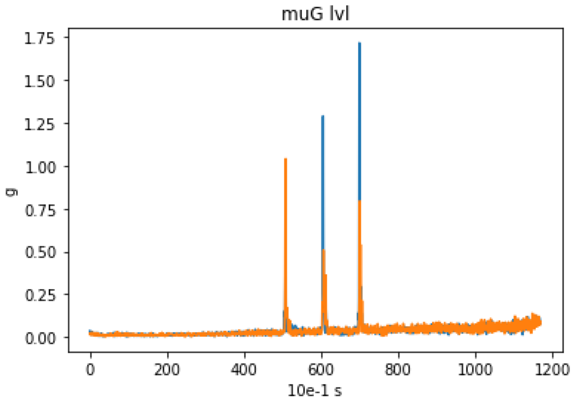

Figure 13, Microgravity level during experiment

The micro-gravity level during experiment was bellow 0.1g , except during three spikes corresponding to Daedalus FFUs ejection. Those spikes had no effect on the experiment due to the short duration and viscosity of the fluid used, that was able to absorb the sudden variation of acceleration.

During micro-g flight phase, the centrifuge has applied the axial acceleration profile shown in Figure 14 to the PMD sponges.

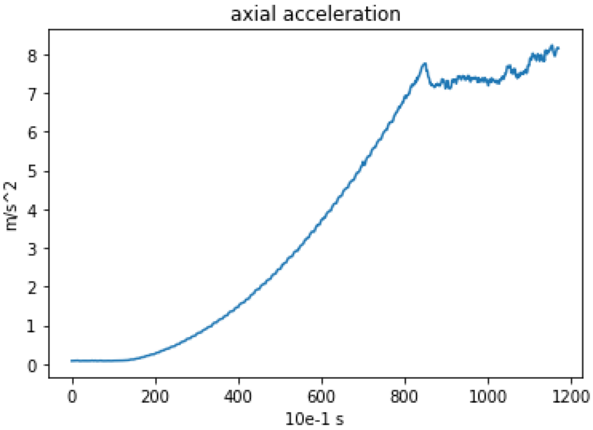

Figure 14, Axial acceleration during experiment

Footage was recorded of the first droplet formation under axial acceleration.

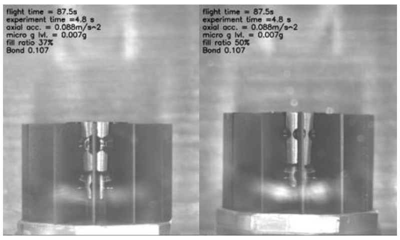

Figure 15: Start of injection

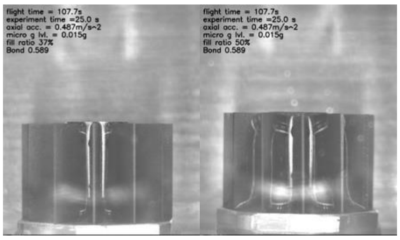

Figure 16: End of injection

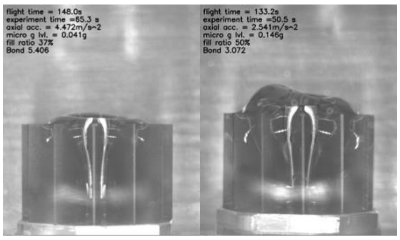

Figure 17: Droplet formation

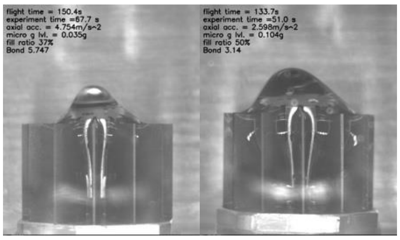

Figure 18: Droplet before detachment

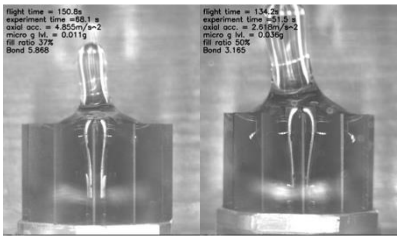

Figure 19: Droplet detachment

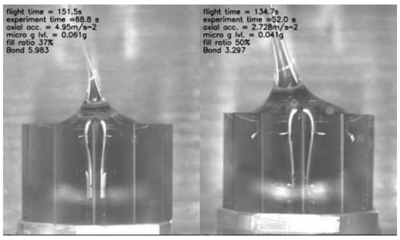

Figure 20: Droplet after detachment

3. Results

The detachment acceleration of the first droplet had been compiled for the simulation and measured for the experimental PMD, then converted to Bond number with eq. 1.

Table 1, summary of results

Fill ratio	Simulation, Bond number at detachment	Experiment, Bond number at detachment
37%	2.32	5.86
50%	1.55	3.17
75%	1.24	***
100%	0.90	***

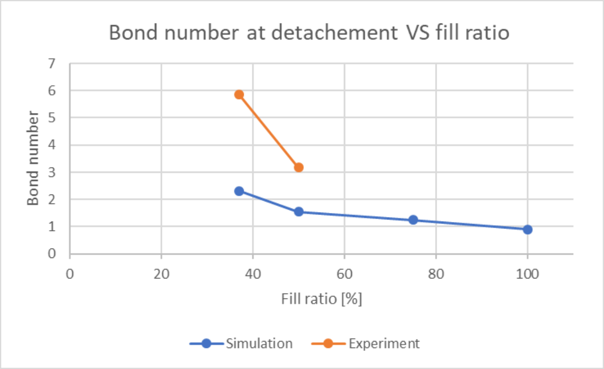

Figure 21, Drop detachment Bond number VS fill ratio, simulation and experimental results

The results seem to follow the same trend between experimental and simulation. However, the lack of experimental points cannot confirm the behaviour.

Bond numbers issued from simulation seem to be under evaluated. A dynamic effect of step by step acceleration variation of the CFD, in opposition of continuous gradual variation during flight can cause this under evaluation.

Further investigations are needed. The simulations will be completed using the real flight boundary conditions.

4. REFERENCES

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