CAESAR – CAPILLARITY-BASED EXPERIMENT FOR SPATIAL ADVANCED RESEARCH ON REXUS-14

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ABSTRACT

CAESAR is a sounding-rocket experiment carried out by students of hepia from HES-SO within the REXUS program. The team has launched on REXUS-14 a capillarity-based experiment to reliably confirm other ground-based experiments. The objective of this flight was to place several sponges in a microgravity environment and acquire images of the fluid distribution around them.

The center element of the experiment, called a sponge, is a propellant management device (PMD) for space vehicles, often used in satellites. It is designed to work even if the vehicle undergoes small accelerations, for example during station-keeping maneuvers.

This flight was the final step to have sufficient data to publish the results of all the researches the team achieved in the past few years. If the results are validated, the team will have a reliable ground based microgravity system to test PMDs.

Key words: REXUS, CAESAR, PMD, sponge, liquid, microgravity, Switzerland, HES-SO.

1. INTRODUCTION

By this experimental campaign, the team was willing to validate theoretical, numerical and experimental data concerning the behavior of liquids in a specific type of a propellant management device (PMD) called a “sponge”.

The theory and its applications are based on a publication from Don E. Jaekle Junior issued in 1993 for the 29th AIAA Joint Propulsion Conference and Exhibit [1].

Sponges, which are radial panel shaped devices, can be used at the bottom of a satellite tank to keep the propellant near the outlet.

These devices are designed to work even if the vehicle undergoes small accelerations, for example during station-keeping maneuvers. The fluid is eccentric but stays on the sponge and near the outlet. Thus the injection system

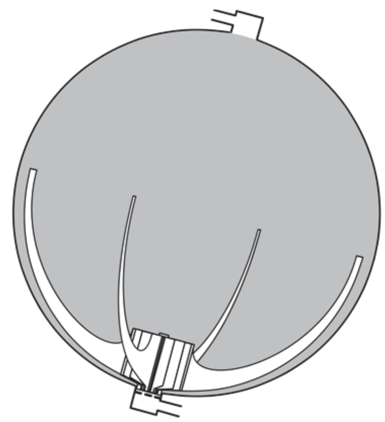

Figure 1. Sponge concept (with 4 vanes) for a satellite tank [1]

of the motor is continuously supplied with the propellant. However, if the vehicle undergoes accelerations over the critical acceleration of the PMD, the fluid will leak out the sponge.

In this document, we will refer to the Bond number. The Bond number is a dimensionless measure of the importance of surface tension forces compared to body forces. A high Bond number indicates that the system is relatively unaffected by surface tension effects; a low number (typically < 1) indicates that surface tension dominates, thus the system is under a micro-gravity environment. Intermediate numbers indicate a non-trivial balance between the two effects.

$$Bo = \frac{\Delta\rho \cdot a \cdot r^2}{\sigma \cdot \cos(\alpha)} \quad (1)$$

$\Delta\rho$: difference in density of the two phases

a : acceleration

r : characteristic length (radius of the fluid between two panels)

σ : surface tension

α : angle of contact between the panels and the fluid

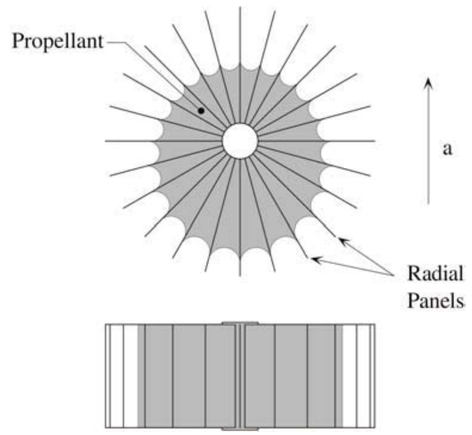

Figure 2. A conventional sponge undergoing an acceleration [1]

This number is used to determine the size of the PMD and the environment conditions. It is also possible to scale the results of all different experiments with the Bond number. By that mean, the team can compare the data of the REXUS flight with the data recorded on ground.

1.1. Experiment background

Professor Roberto Putzu, with the support of two students[1], created a ground-based test facility by buoyancy in 2011 for the observation of this particular phenomenon. In the same year, Eric Zumbrunnen designed another system by magnetic levitation to perform the same experiment. All these experiments were related to the one launched on REXUS-14.

These ground-based systems are cheaper and easier to use than a sounding rocket, a parabolic flight or a drop tower, so they will be very useful to make progress in this particular domain of science, if the results are validated by the REXUS flight.

The CAESAR team, lead by the authors, was created to reliably confirm that the results obtained on ground are valid. In order to perform this validation, they designed and built the experiment described in this document.

In particular, the team was interested in identifying experimentally the behavior of the liquid under Bond numbers approximately equals to 1, when the theory foresees two possible equilibrium states of the liquid and vapor phases arrangement. As no general public document is available and the only publications are theoretical, the team also wished to publish its results as widely as possible.

[1]Gregory Sokolowski and Alban Leandri

2. EXPERIMENT OVERVIEW

CAESAR experiment consisted basically in placing four PMD samples in a microgravity environment and in observing them with video cameras.

Four PMD samples were integrated into a so called "experiment plate", alongside with their injection system. When the rocket was in microgravity conditions, the injection system filled all the sponges with a liquid[2] having a low contact angle with the material of the sponges (that means that a drop of the liquid will spread on the solid). Each PMD had a different fill ratio, as shown in Tab. 1. This design choice was made in order to collect as much data as possible.

Table 1. Liquid volumes

Sponge #	Volume (ml)	Fill ratio
1	1.125	11.1%
2	1.625	16.0%
3	2.125	20.9%
4	2.625	25.8%
TOTAL	7.500	

A motor integrated into the main shaft (see Fig. 3) has then caused the experiment plate to rotate, in order to impose a radial acceleration on the sponges. Four different accelerations were imposed on the experiment plate to collect more data. Thus, with four accelerations and four different fill ratios, the team recorded sixteen different experiment cases.

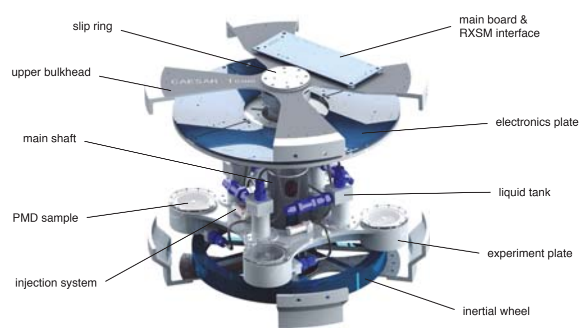

Figure 3. Assembly overview

Each PMD has been observed by a video camera mounted on the "electronics plate". This plate was directly connected to the main shaft, so it was rotating too: the optical axis of each camera was aligned with the center of the sponge beneath it.

The absolute acceleration imposed on the sponges has been measured by four accelerometers on the electronics plate. These accelerations levels were designed in accordance with the Bond numbers defined in past experiments to ensure the principle of similarity, allowing the comparison of the different results.

[2]PDMS: Polydimethylsiloxane (a silicone oil)

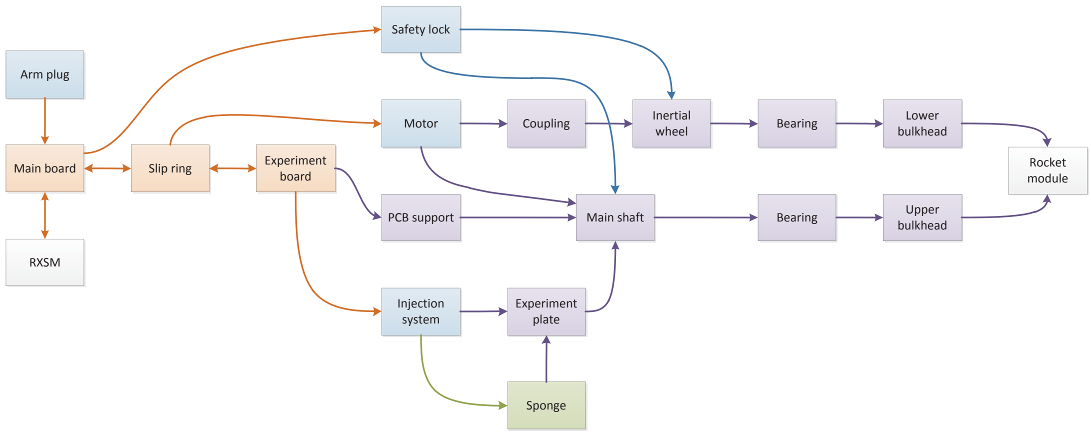

Figure 4. Experiment block diagram

The electronics stored the data on board and sent a part of it to the ground (via the REXUS Service Module interface). The signal transmission between the electronics and the rocket was established through a slip ring.

To reduce the torque transmitted to the rocket, a contra-rotative inertial wheel was integrated beneath the experiment plate. From a mechanical point of view, the whole system was connected to the rocket via a low-friction bearing on each bulkhead. The system was thus isolated from the rocket and the rotation of the experiment plate caused the inertial wheel to rotate the other way.

3. EXPERIMENT SETUP

The CAESAR module consisted of two major subsystems: the experiment and the system to control it. The "experiment plate", as described in Section 2, consisted of four sponges (green) connected to their injection system. The control system was partly mechanical (purple) and partly electronics (orange), as described in details in Fig. 4 and in the following sections. The entire module was linked to the structure of the rocket with an upper and a lower bulkhead. For the electronics, the link with the RXSM was done through a D-Sub connector attached on the main board.

3.1. Experiment

As it has been decided to have four sponges, all the controls of the experiment were also multiplied by four.

The "experiment plate" consisted mainly of the sponges, manufactured directly in a titanium plate to ensure the same state of the material for each test cell and to reduce the amount of fixations around them. Each test cell had its own independent injection system to ensure the reliability of the others in case of failure.

For the same reason, each injection system was commanded by its own experiment board. The liquid tank of this system was attached to the experiment plate, which was screwed on the main shaft. The experiment boards were screwed on the PCB[3] support plate, referred as the "electronics plate", which was also connected to the main shaft. The experiment boards carried the cameras, the lights (LED), the flash memories and the electronics to records all these data.

3.2. Controls

The experiment was driven by a motor placed in the center of the main shaft. The stator was fixed in the main shaft and the rotor was connected through a semi-elastic coupling to an inertial wheel designed to compensate the torque transmitted to the rocket from the experiment.

This inertial wheel was linked to the lower bulkhead with a bearing and the bulkhead was maintained by four brackets attached to the skin of the rocket. On the other end of the module, the main shaft was connected to the upper bulkhead with a bearing. This bulkhead was also connected to the skin with four brackets. This configuration ensured that minimal torques and forces were transmitted to the rocket, because the CAESAR module was partially independent from the rocket.

For the electronics, the experiment boards were connected altogether with a CAN[4] bus and to the main board through a slip ring fixed on the center of the main shaft. The main board was mounted directly on the top of the upper bulkhead. It was connected to the RXSM, the disarm plug and the locking system. It has ensured data and power transmission to the experiment boards, the unlocking of the module after the ascent phase and, thanks to the disarm plug, the management of the injection system during the tests.

[3] Printed Circuit Board
[4] Controller Area Network

4. THE REXUS-14 FLIGHT

The experiment has been successfully launched on REXUS-14 from Esrange in Sweden on the 7th of May 2013. During this short flight, all the systems of the experiment seemed to work as planned. Especially all the housekeeping data were received.

However, after the recovery, it has been discovered that a problem occurred in the experiment located just above CAESAR and caused its complete failure at T+1.5 seconds. The CAESAR team performed an investigation to determine the effect of this failure on the CAESAR experiment.

First of all, it has been confirmed that all the injection systems worked. So, from a technical point of view, the experiment was a success. Nevertheless, it was discovered during the investigation that some metallic particles were projected on one of the PCBs. This issue is developed in the following section.

4.1. Issue

These particles were spread from the upper module (i.e. Gekko experiment) trough the CAESAR module. After investigations, it seems that a current peak in a soldering caused its melting and the spreading of these hot metallic particles all over a quarter of the top of the CAESAR experiment. In particular, as shown in Fig. 5, over the main board and the experiment board #3.

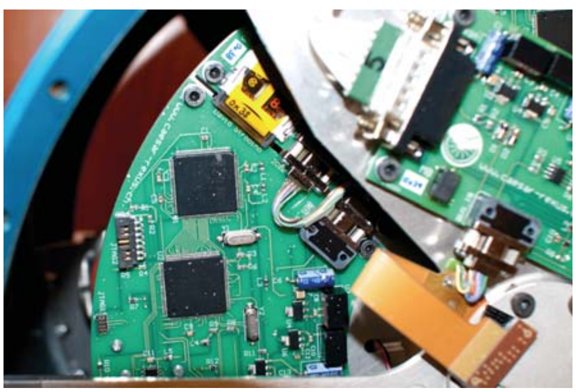

Figure 5. Metallic particles on the experiment PCB

Globally, these particles were stopped by the three layers of silicon coating protecting all the PCBs of the CAESAR experiment. Nevertheless, it has been discovered that a small particle (circled in Fig. 6) melted the coating and caused the failure of the writing process on the SD card #3. Thus, no data were recorded for this experiment board, which means the loss of a quarter of the overall expected data.

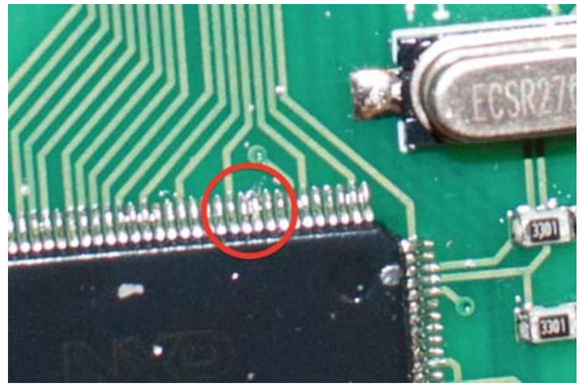

Figure 6. Zoom on the μ-controller of the 3rd experiment board

5. RESULTS

As explained, the purpose of the REXUS flight was to validate the data recorded on ground. So the team was expecting results similar to the ones observed on ground, which were already similar to the theory of the phenomenon, as shown in Fig. 2.

All the results presented below are in their preliminary form; moreover, only some samples are presented. The complete analysis and the comparison of all the different data will be the subject of a forthcoming publication.

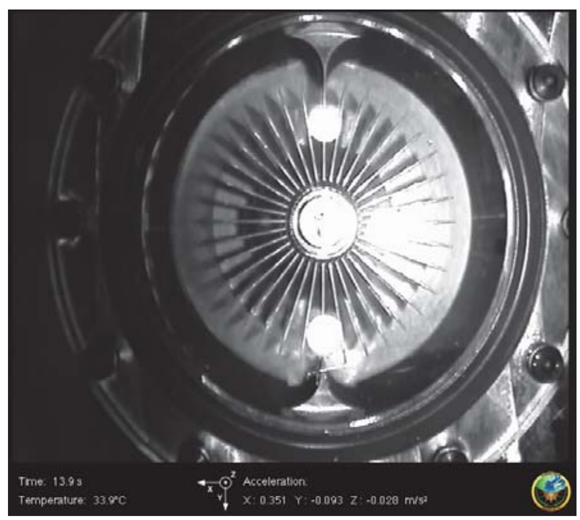

Figure 7. Experiment #1 – During injection

Each figure includes a screen overlay, written directly during the flight, to guarantee that the data from the sensors used the same timeline as the images from the video cameras, without the need of post-processing after the flight.

5.1. Injection

The liquid was injected into the sponges right after the nosecone separation. The injection time was set to 10 seconds during the test phase of the injection system. This time was sufficient to inject all the liquid, with a margin in case of an unexpected delay.

Fig. 7 and 8 show the experiment cells a few seconds after the injection.

Figure 8. Experiment #2 – During injection

5.2. Stabilized acceleration

The main results of the experiment are the four different acceleration steps determined in Section 2. Fig. 9 shows the experiment cell #1 during one of these steps.

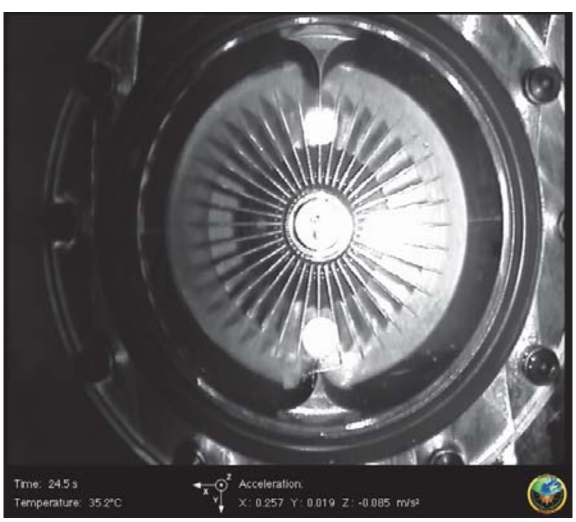

Figure 9. Experiment #1 – Stabilized acceleration

5.3. Maximal acceleration

Fig. 10 and 11 show the experiment cells during the last step, at the maximal acceleration. These particular results are easily observable as the liquid is clearly eccentric.

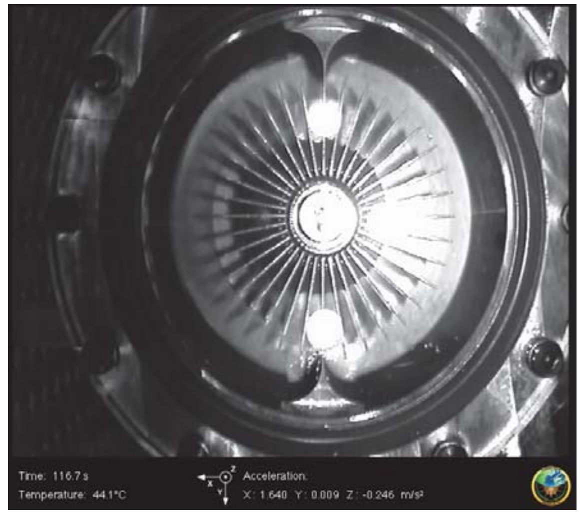

Figure 10. Experiment #1 – Maximal acceleration

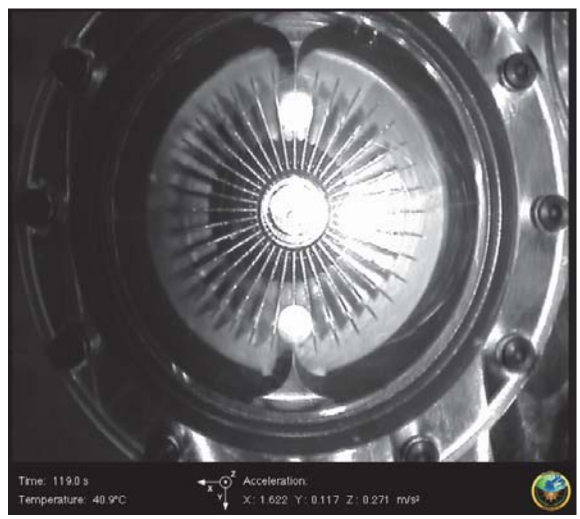

Figure 11. Experiment #2 – Maximal acceleration

6. FUTURE OF THE PROJECT

In the next months, Professor Roberto Putzu will perform the analysis of all the data recorded on the experiment during the REXUS-14 flight. With these analyses, it will be possible to compare all the theoretical, numerical and experimental data collected during the past years.

If the comparison proves that the ground system by buoyancy can be used for further work, it will be possible to do propellant management researches on ground at low cost.

The work to be done on the data of the CAESAR experiment is mainly the segmentation of the liquid interface. Some samples of the preliminary analyses are presented bellow.

Figure 12. Experiment #1 – Stabilized acceleration, with segmentation

Figure 13. Experiment #1 – Maximal acceleration, with segmentation

However, due to the relatively low image contrast and the shadow of the panels, the best segmentation was achieved by hand, despite the fact that it was planned to use software image processing.

The liquid shape has been extracted, using polar coordinates from the center of the sponge, with a MATLAB script that rotated the image of 1° at a time. For each rotation angle, the end of the liquid shape was pointed along the horizontal axis. The resulting contour is shown in Fig. 12 and 13.

From a qualitative point of view, the results seem to be similar to the theory. Nevertheless, further analyses will give the quantitative aspect of this similitude.

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ABBREVIATIONS

CAN	Controller Area Network (data bus)
PCB	Printed Circuit Board (electronic board)
PMD	Propellant Management Device
PDMS	Polydimethylsiloxane

REFERENCES

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