Published in the Proceedings of the 22nd ESA Symposium on European
Rocket and Balloon Programmes and Related Research, 7-12 June 2015,
Tromso, Norway, which should be cited to refer to this work.

PROPELLANT MANAGEMENT IN MICROGRAVITY – FURTHER ANALYSIS OF AN EXPERIMENT FLOWN ON REXUS-14

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ABSTRACT

This paper is about the further analysis of an experiment named CAESAR (stands for Capillarity-based Experiment for Spatial Advanced Research): a sounding rocket experiment carried out by students of hepia within the REXUS program. The authors have launched on REXUS-14 a propellant management experiment based on capillarity to reliably confirm other ground-based experiments. In the framework of the present work, the authors present the comparison of CAESAR experimental data with theoretical profiles provided in literature. The objective of this flight was to place several Propellant Management Devices (PMD) in a microgravity environment and acquire images of the fluid distribution around them.

The main element of the experiment, called a sponge, is a PMD for space vehicles, often used in satellites. This radial panel shaped device can be used at the bottom of a satellite tank to keep the propellant near the outlet. It is 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, so the injection system of the motor is continuously supplied with the propellant.

As previously published, the authors have created a buoyancy test bench and have designed another system by magnetic levitation to perform the same experiment on earth. These systems are easier to use and less expensive than a sounding rocket, a parabolic flight or a drop tower (i.e. other system to obtain microgravity on earth), so they will be very useful to make progress in this particular domain of science. They will also allow universities with small funds to work within this spatial field.

A previous publication showed, from a qualitative point of view, a good agreement between experiments and theory; however in this paper quantitative comparisons are given. With this demonstrated, hepia can validate its buoyancy test facility with real flight tests.

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

1. INTRODUCTION

Although in a gravitational environment a liquid in a tank is known to take its lowest potential energy configuration settling at the bottom of the enclosure, in a tank placed in microgravity the lowest potential energy configuration is more difficult to identify. In fact, in this configuration the gravitational energy decreases and is overcome by surface tension.

Active devices such as bladders are used in the space propellant management, but when long time compliance is required with oxidizing liquids, when lightweight structures are desired and when high reliability (no moving parts) is required by the mission, the propellant management in spacecrafts is performed by passive devices orienting the liquid towards the outlet port by means of surface tensions. These devices are known in the space propulsion community as PMDs (Propellant Management Devices).

According to the mission profile, the PMD can be organized in different architectures, summarized by Jaekle in four articles available in literature [1, 2, 3, 4]; each architecture characterized by several performances. Among the different architectures and performances, the authors focused on the capacity of the "sponge" type PMD to retain a liquid when subjected to steady lateral accelerations simulating station keeping maneuvers.

2. PHYSICS BACKGROUND

In the PMD technology, a "sponge" is a device composed of a series of radial inwards tapering panels, aimed at collecting at its center the amount of liquid necessary to perform a mission maneuver (see Fig. 1).

One of the driving requirements to be imposed to a sponge device in the framework of a PMD design is its ability to provide this amount of bubble-free propellant under maneuver imposed accelerations.

Theoretical 2D procedures exist to investigate the liquid shape within a sponge under known accelerations [1]. These procedures, that allow the determination of the

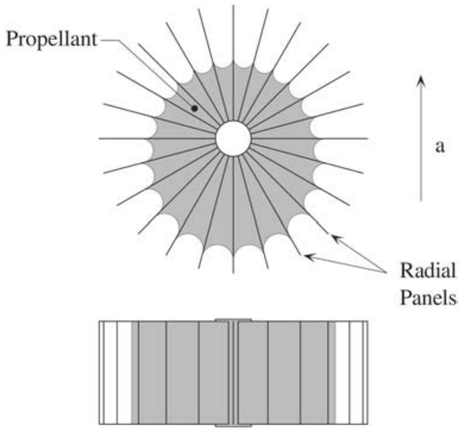

Figure 1. A "sponge" undergoing an acceleration. [1]

PMD volume retention capability, are based on the Bond number, which is the ratio between hydrostatic and capillary forces:

$$Bo = \frac{\text{hydrostatic}}{\text{capillary}} = \frac{\rho\, a\, r_{ext}^2}{\sigma\ \cos(\theta)} \tag{1}$$

where ρ is the density of the liquid, a is the maneuver acceleration, r_{ext} is the external radius of the sponge, σ is the surface tension of the test liquid and θ is the contact angle of the liquid with the solid. Low Bond numbers represent capillary dominated configurations, whereas high Bond numbers represent hydrostatics dominated configurations.

The static liquid shape will not only depend on the Bond number, but also on the fill ratio. The amount of propellant present in the sponge will change the profile of the liquid in the device. For this reason, the fill ratio is here defined as the ratio between the held liquid volume V_{held} and the sponge overall volume $\pi\, r_{ext}^2\, h$:

$$FR = \frac{V_{held}}{\pi\, r_{ext}^2\, h} \tag{2}$$

The present work presents the comparison between the shapes obtained by the theory presented by Jaekle and the experimental liquid shapes obtained by the CAESAR experiment in the REXUS-14 flight. Data are presented for three fill ratios and for three Bond numbers.

In his article, Jaekle identifies a limit acceleration, beyond which two stable shapes of the liquid coexist. The presented work only focuses on accelerations below this limit acceleration.

3. CAESAR PROJECT

The idea of initiating the CAESAR project inside the REXUS program came from the creation of a ground test bench to simulate the effects of microgravity on liquid flows inside sponge PMDs.

With the experiment launched on REXUS-14 on the 7th of May 2013, the goal of the authors was to confirm the results obtained experimentally on ground by a flight in real microgravity condition.

3.1. REXUS program

The REXUS/BEXUS program [5] allows students from universities and higher education colleges across Europe to carry out scientific and technological experiments on research rockets and balloons. Each year, two rockets and two balloons are launched, carrying up to 20 experiments designed and built by student teams.

REXUS experiments are launched on an unguided, spin-stabilized rocket, powered by an Improved Orion motor with 290 kg of solid propellant. It is capable of taking 40 kg of student experiment modules to an altitude of approximately 90 km. The vehicle has a length of around 5.6 m and a body diameter of 35.6 cm (14 inches).

4. EXPERIMENT OVERVIEW

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

Four sponges were integrated into a so called "experiment plate", alongside with their injection system. When the rocket was in microgravity conditions, the injection system filled the sponges with a liquid having a near-zero contact angle with the material of the sponges. Each PMD had a different fill ratio. This design choice was made in order to collect as much data as possible.

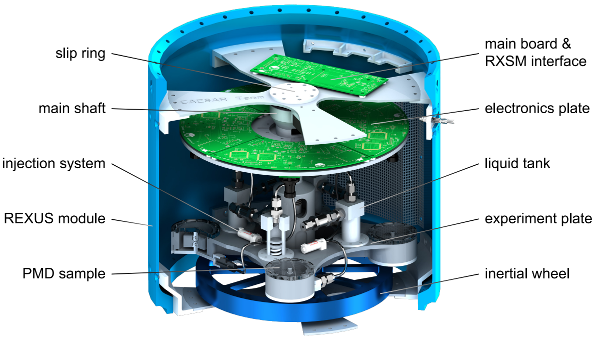

Figure 3. Assembly overview.

A motor integrated into the main shaft (see Fig. 3) has then been operated, causing the experiment plate to rotate, in order to impose a radial acceleration on the sponges.

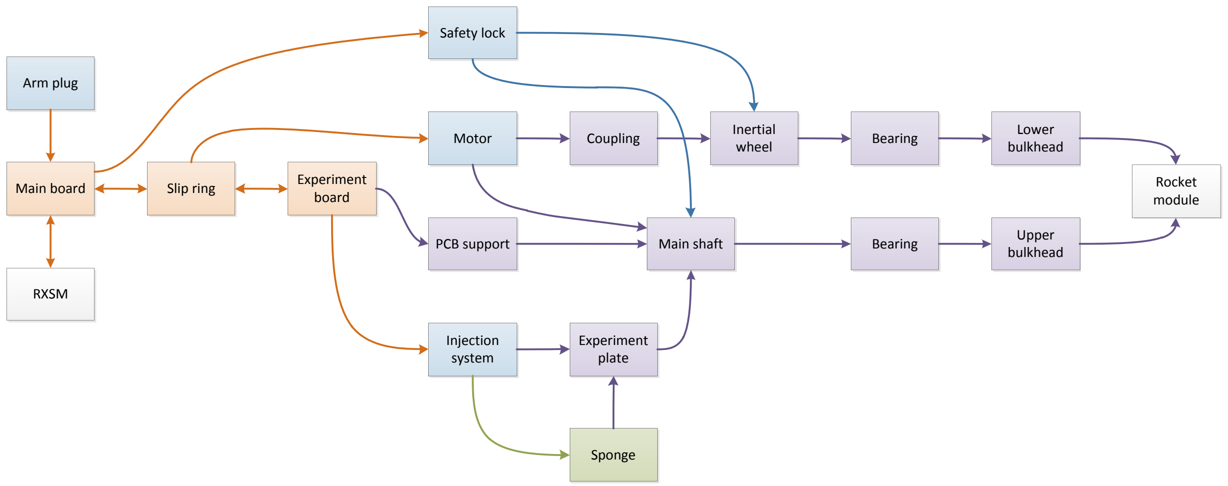

Figure 2. Experiment block diagram.

Several accelerations were imposed on the experiment plate to collect a maximum of sixteen experiment cases.

Each PMD was observed by a video camera mounted on the "electronics plate", which was connected to the main shaft and rotating: the optical axis of each camera was aligned with the center of the sponge beneath it. The absolute acceleration imposed on the sponges was measured by four accelerometers on the electronics plate. These accelerations levels were defined in accordance with the Bond numbers used in past experiments to ensure the principle of similarity, allowing the comparison of the different results.

The electronics stored the data on board and sent a part of it to the ground via the REXUS Service Module (RXSM) 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 (see Figs. 2 and 3). The system was thus isolated from the rocket and the rotation of the experiment plate caused the inertial wheel to rotate the other way.

Unfortunately an electrical failure in the experiment located just above CAESAR caused the spreading of hot metallic particles all over a quarter of the top of the CAESAR experiment. In particular over the main board and the experiment board #3. Globally these particles were stopped by the three layers of silicon coating protecting all the PCBs of the experiment; nevertheless a small particle melted the coating and caused the failure of the writing process on the SD card #3 (more details can be found in [6]). Thus no data were recorded for this experiment board, which means the loss of a quarter of the overall expected data.

4.1. Test setup

The liquid shapes presented in the current article were identified on sponges machined in full titanium by wire Electrical Discharge Machining (EDM). Dimensional detail of a test cell can be found in Fig. 4.

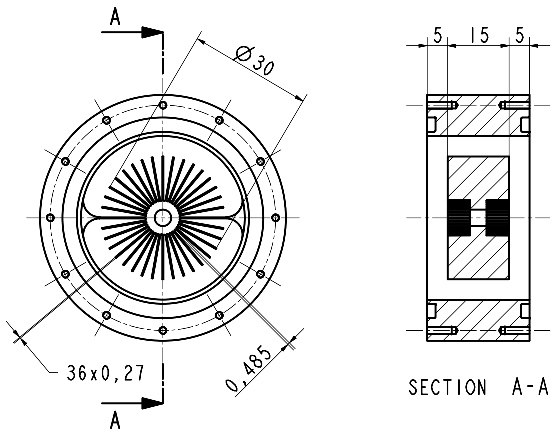

Figure 4. Dimensional detail of a test cell.

The liquid used in the experiment was PDMS[1]. The fluid had near-zero contact angle θ with respect to titanium EDM machined flat test samples, so that the parameter $\cos(\theta)$ in Eq. 1 was considered to be 1 in the analyses. Finally, in order to be in accordance with the theory exposed by Jaekle, liquid passage was guaranteed between the sponge gaps by leaving a free space between the central pole and the panels.

The results presented in this paper correspond to the conditions stated in Table 1.

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[1] PDMS: Polydimethylsiloxane (a silicone oil)

Table 1. *Summary of the result figures.*

Experiment:	#1	#2	#4
Fill ratio:	16%	11%	4%
$Bo = 1.43$:	Figs. 5, 8	Figs. 6, 11	Figs. 7, 14
$Bo = 5.73$:	Figs. 5, 9	Figs. 6, 12	Figs. 7, 15
$Bo = 13.3$:	Figs. 5, 10	Figs. 6, 13	Figs. 7, 16

5. RESULTS AND DISCUSSION

For the three fill ratios, the results are here presented as follows:

- At first, the three pictures showing the microgravity experimental behavior of the sponge are shown for the different Bond numbers. The acceleration is here directed downwards. For the sake of clarity, on these pictures red dots highlight the profile used for the comparison with the theoretical results.
- Subsequently, the comparison between theoretical and experimental results are presented together with an error histogram for the three Bond numbers.
  - On the left pictures, the actual comparison between the experimental and theoretical profiles is presented.
  - Considering the profile in polar r and α coordinates, the authors evaluated the relative error in radius for all the profile points. On the right pictures the error histogram shows the number of occurrences for every relative error. It has to be considered that, due to the difficulty to identify the actual profile in the lowest part of the sponge, for this evaluation the points between $\alpha = 150°$ and $\alpha = 210°$ were excluded.

For the two high fill ratios and for the two lower Bond numbers (Figs. 8, 9, 11 and 12), the theoretical prediction appears to predict quite accurately the profile; the errors never exceeding 7% in absolute value.

Considering the lowest fill ratio (Figs. 14, 15 and 16), from a qualitative point of view a good agreement is observed between theoretical and experimental results. Nevertheless, the camera frames show a clearly asymmetrical profile, indicating a misbehavior in the spreading of the liquid. This can be related to insufficient cleaning between the panels: where the gaps are smaller an undesired deposit can be difficult to evacuate by cleaning procedures. Therefore the local contact angles and capillary forces can be significantly modified and influence the local position of the experimental points.

Considering the highest Bond number and the highest fill ratios (Figs. 10 and 13), a more important difference between the two profiles is observed. Two main reasons are deemed to be at the origin of this difference:

- The liquid communication between the panels is guaranteed by a narrow gap disposed at the center of the sponge. Because of the acceleration change between the different Bond numbers, a certain time is necessary for the liquid to flow from one gap to another. According to the investigations, the experiment probably didn't have enough time to achieve the equilibrium position.
- During the final flight phases, the accelerometers mounted on the experiment board showed the existence of growing undesired fluctuations, also highlighted by an unsteady behavior of the liquid in the motion capture. It is therefore not possible to interpret the visual results under the light of the steady state theory depicted by Jaekle.

6. ACKNOWLEDGMENTS

The authors acknowledge RUAG Space Switzerland, +GF+ AgieCharmilles, maxon motor, HES-SO and hepia for their support.

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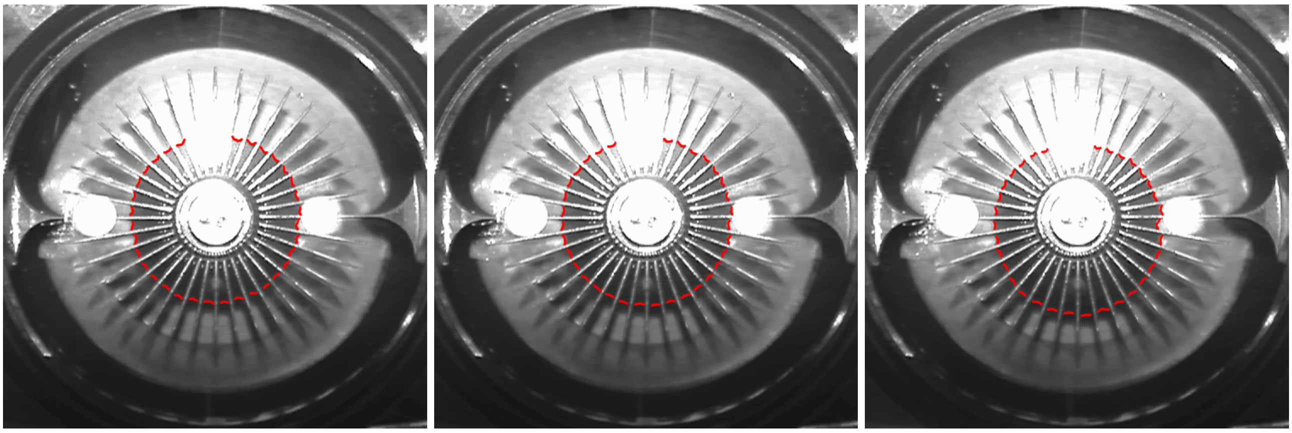

Figure 5. Experiment #1 – REXUS data with segmentation. FR = 16%. Bo = 1.43 (left), 5.73 (center), 13.3 (right).

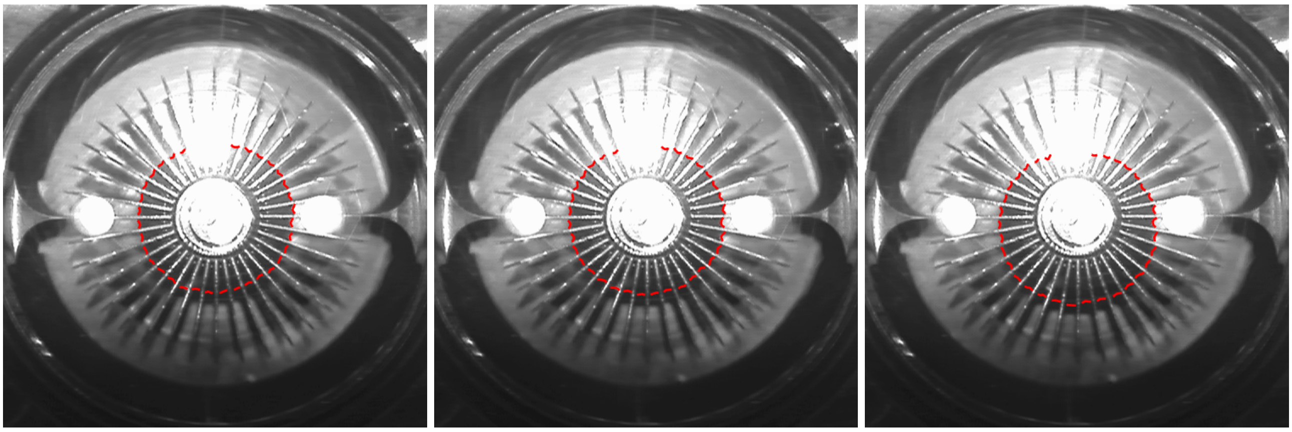

Figure 6. Experiment #2 – REXUS data with segmentation. FR = 11%. Bo = 1.43 (left), 5.73 (center), 13.3 (right).

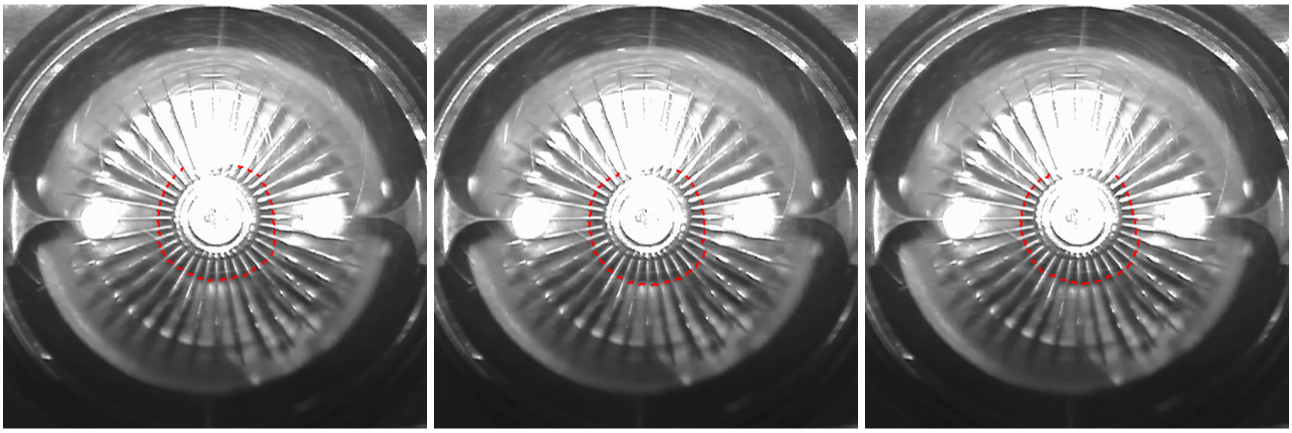

Figure 7. Experiment #4 – REXUS data with segmentation. FR = 4%. Bo = 1.43 (left), 5.73 (center), 13.3 (right).

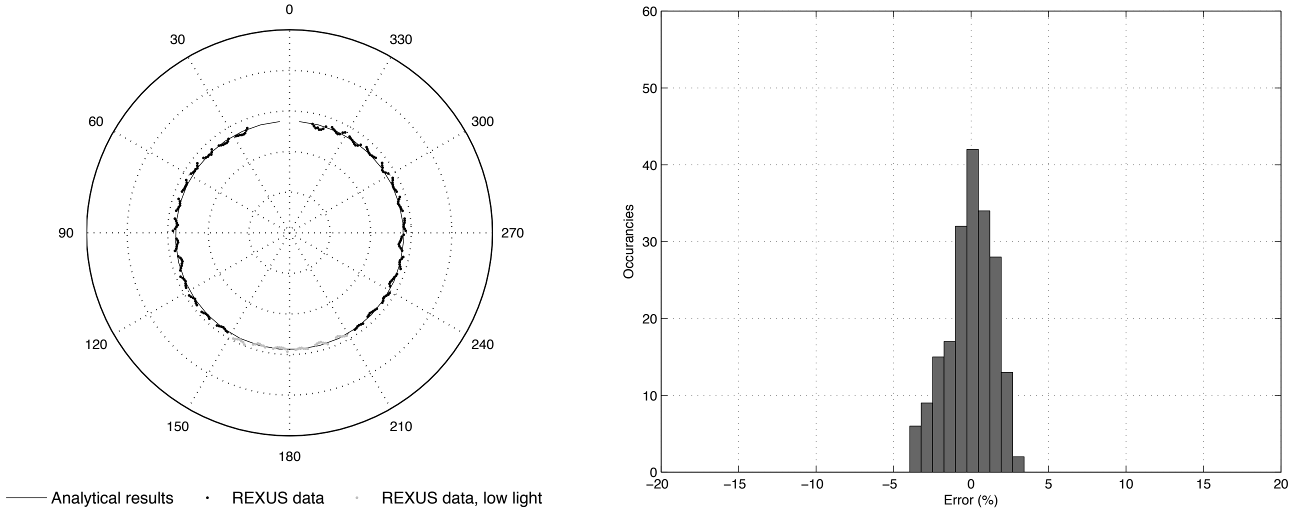

Figure 8. Experiment #1 – Analytical and experimental results, shape (left) and errors (right). FR = 16%. Bo = 1.43.

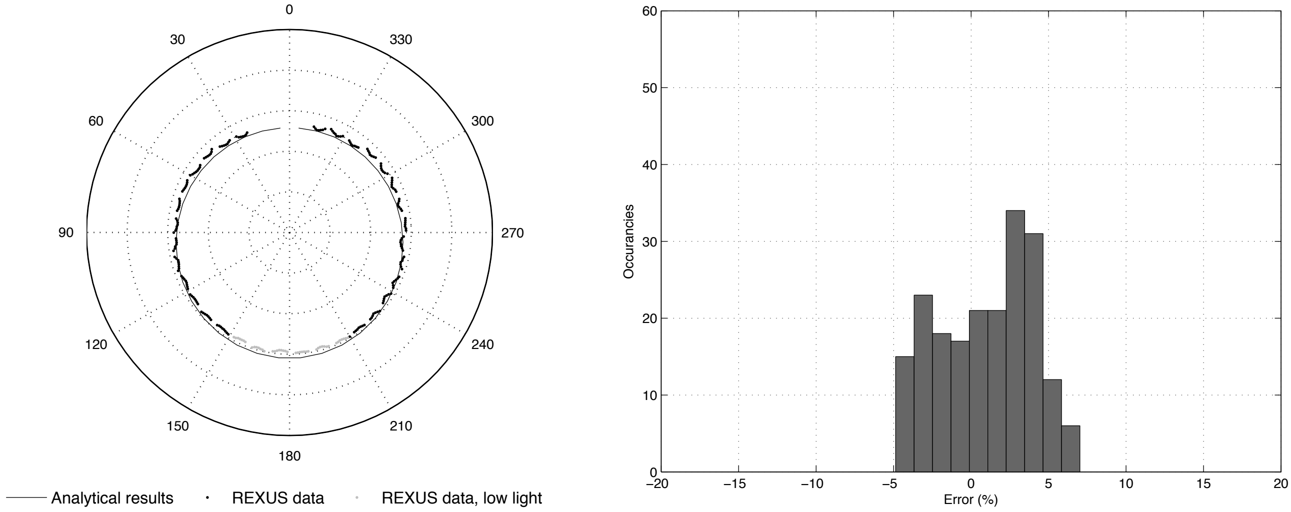

Figure 9. Experiment #1 – Analytical and experimental results, shape (left) and errors (right). FR = 16%. Bo = 5.73.

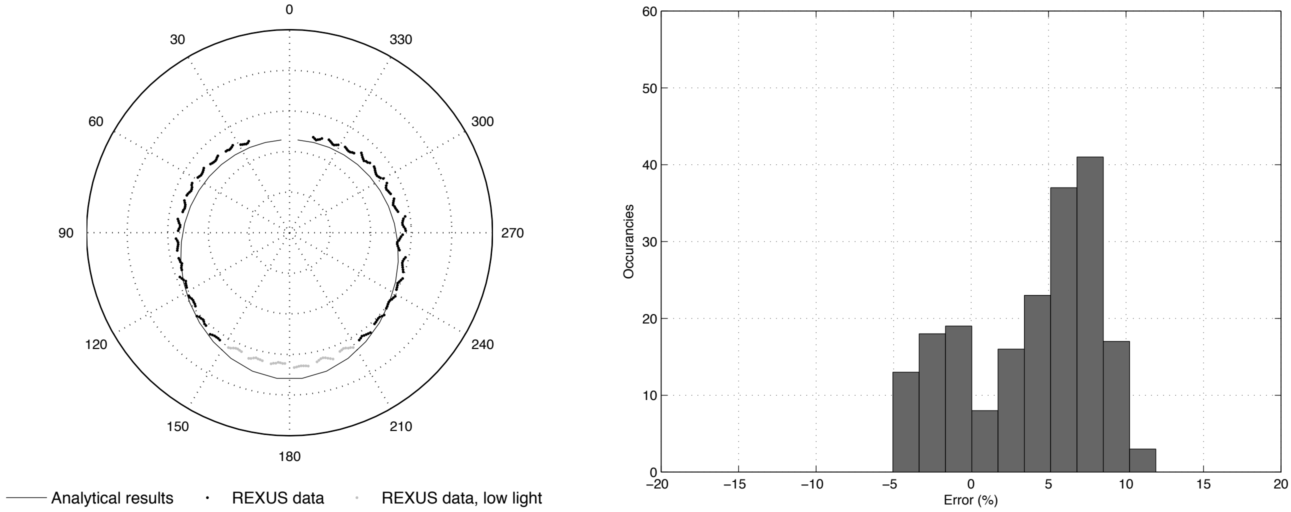

Figure 10. Experiment #1 – Analytical and experimental results, shape (left) and errors (right). FR = 16%. Bo = 13.3.

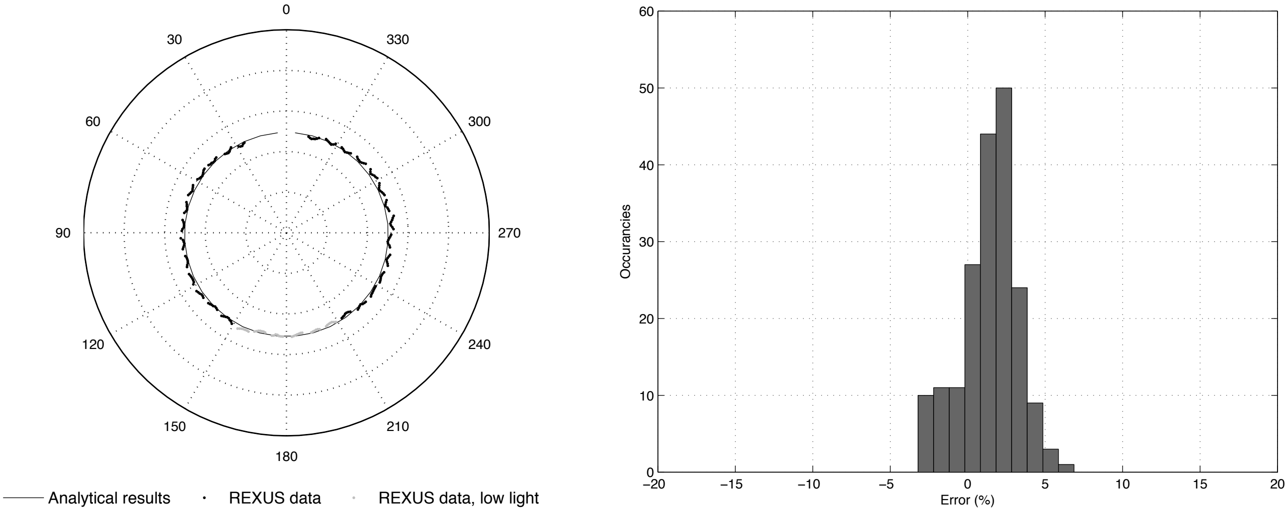

Figure 11. Experiment #2 – Analytical and experimental results, shape (left) and errors (right). FR = 11%. Bo = 1.43.

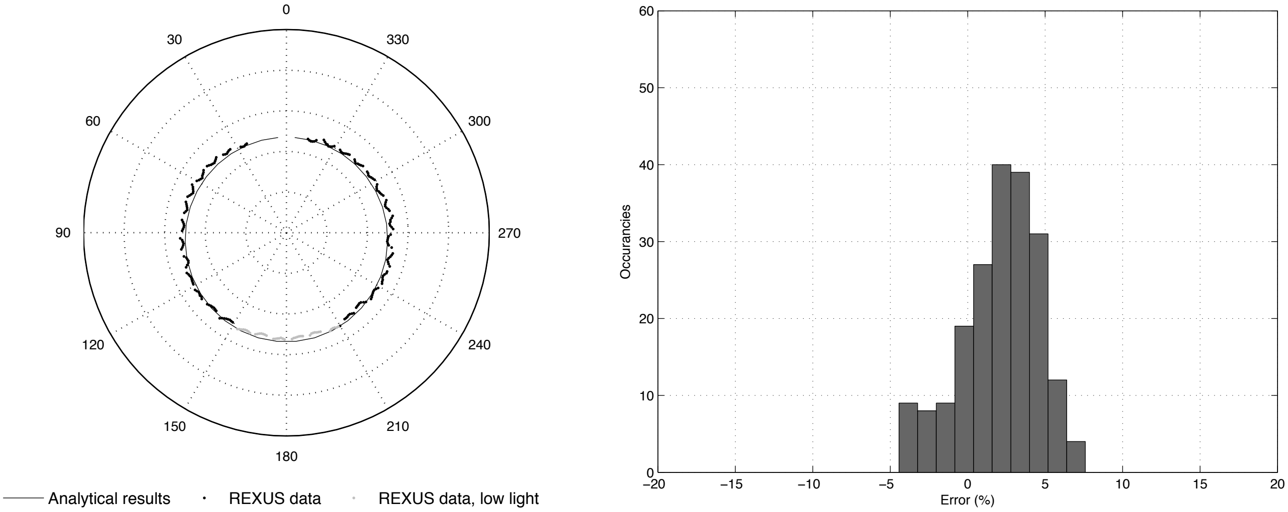

Figure 12. Experiment #2 – Analytical and experimental results, shape (left) and errors (right). FR = 11%. Bo = 5.73.

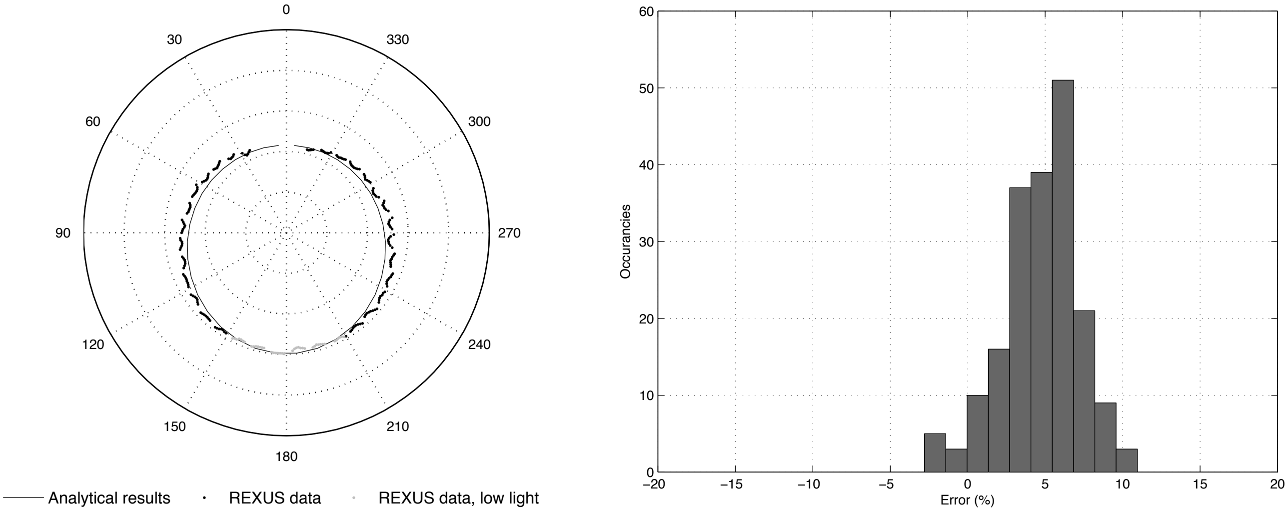

Figure 13. Experiment #2 – Analytical and experimental results, shape (left) and errors (right). FR = 11%. Bo = 13.3.

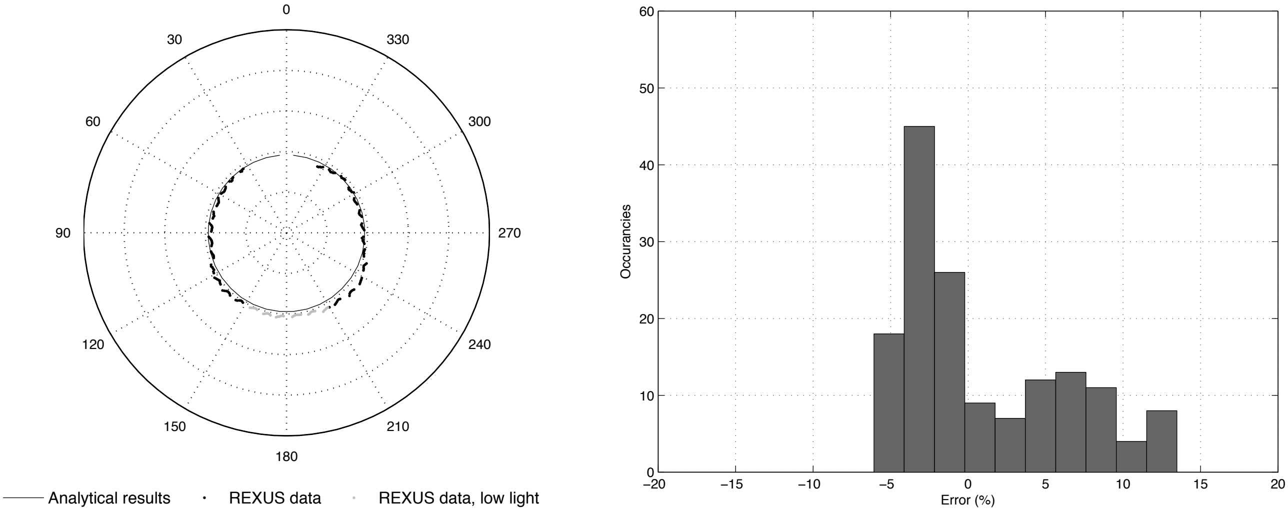

Figure 14. Experiment #4 – Analytical and experimental results, shape (left) and errors (right). FR = 4%. Bo = 1.43.

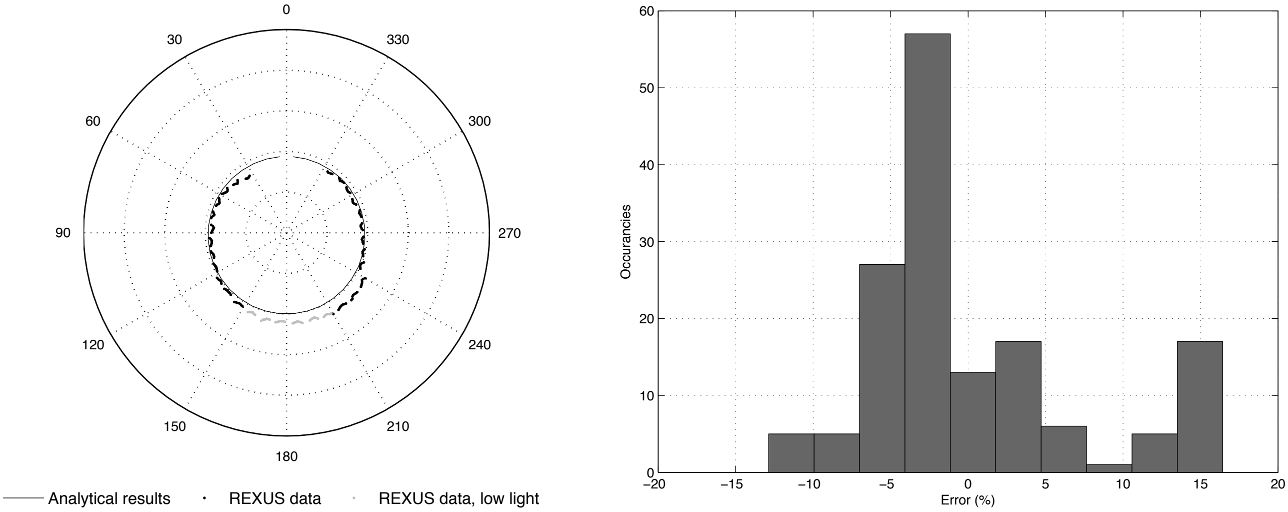

Figure 15. Experiment #4 – Analytical and experimental results, shape (left) and errors (right). FR = 4%. Bo = 5.73.

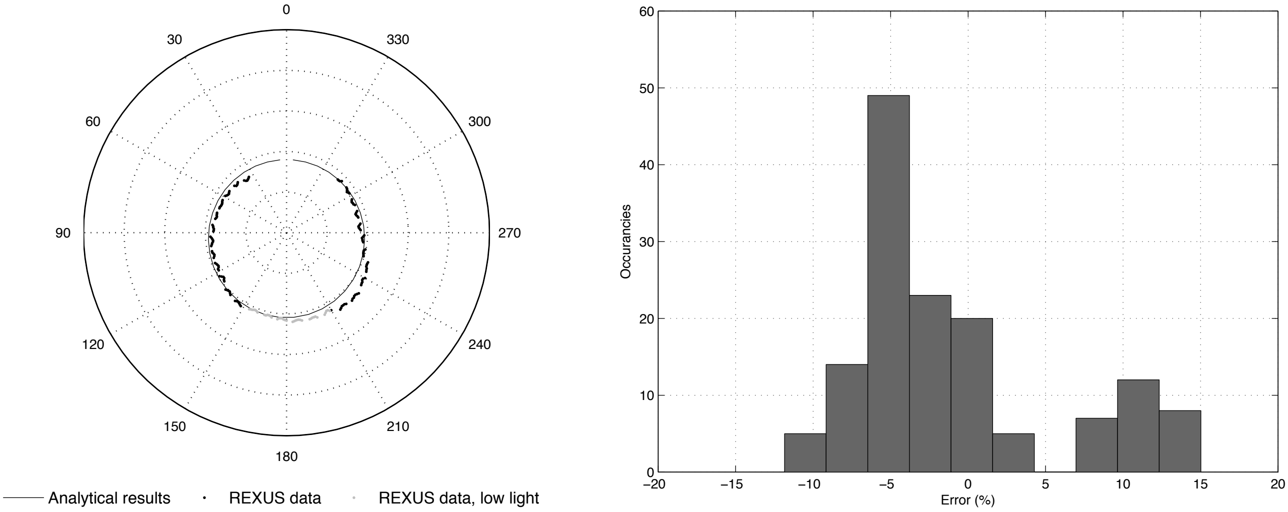

Figure 16. Experiment #4 – Analytical and experimental results, shape (left) and errors (right). FR = 4%. Bo = 13.3.