Supporting an ISS experiment as PhD students: a case study of the PARTICLE VIBRATION project

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Abstract

This paper provides an insight into the involvement of two PhD students in the PARTICLE VIBRATION project, a multiphase fluid experiment, also known as, “Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity” (T-PAOLA) to be launched on the International Space Station by the end of 2022. The project aims to identify self-organization phenomena in dispersed phase flows when vibrations are applied to the system. It will therefore underpin the development of new contactless particle manipulations and materials processing strategies. In this short paper, the work of two PhD candidates, working within the T-PAOLA project framework, is discussed. In doing so, the various research activities undertaken are highlighted, both experimental and numerical, as is the peripheral or supporting research being undertaken by both students in order to expand the scope of the project and identify new lines of enquiry regarding convection-based control mechanisms.

Keywords

Microgravity, Thermovibrational convection, Particle aggregation, ISS experiment, T-PAOLA project

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Acronyms/Abbreviations

ESA	*European Space Agency*
E-USOC	*Spanish User Support and Operations Centre*
MSG	*Microgravity Science Glovebox*
ISS	*International Space Station*
SODI	*Selectable Optical Diagnostic Instrument*
T-PAOLA	*Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity*
TVC	*Thermovibrational Convection*

1. Introduction

Working on a space experiment to be launched on the International Space Station (ISS) is the dream of many mechanical and aerospace engineering students. These opportunities are however difficult to come-by as the level of expertise required to undertake such projects is significant, and often beyond the skills of postgraduate students. Although significant efforts have been made by organizations such as ESA Academy to make altered gravity and space platforms more accessible to students, contributing effectively to projects of such a kind and scale remains a challenge. The T-PAOLA project (Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity, the corresponding NASA/ESA opsnom being "Particle Vibration"), however, has enabled two PhD students from the University of Strathclyde to immerse themselves in a concrete space experiment, leading to significant benefits for both the students and the project itself. In the following, first the scientific context of the experiment [1]–[4], the structure of the research team and the other stakeholders (space agencies and payload developer) are introduced. Then, the specific activities undertaken by the students to directly support the project are described, followed by a more general presentation of their respective research interests and results. These align with the general goals of any microgravity-related project, namely, a meaningful extension of current state of knowledge through the execution of a well-defined series of space experiment and the definition of other experiments to be executed in the future to fill the remaining gaps (see e.g. refs [5], [6]).

2. Scientific objective and team

2.1. Scientific objective

The T-PAOLA project consists of performing multiphase fluid dynamic experiments onboard the ISS. These experiments will investigate how a set of particles dispersed in a Newtonian liquid can accumulate and form well-ordered structures. Indeed, on earth, the behaviour of particle-fluid mixtures is constrained due to gravity leading to flotation or sedimentation of the particles. Once gravity is removed, the dispersed particles are not forced to separate and exploring self-assembly principles becomes possible. By studying these surprising phenomena under microgravity conditions, T-PAOLA aims to pave the way to innovative applications in chemistry, physics, biomaterials, inorganic material science and eventually nanotechnologies.

The flow that facilitates this particle aggregation is known as thermovibrational convection (TVC). This type of convection is a variant of standard buoyancy convection where steady gravitational acceleration is replaced with vibrations (see Figure 1). When subjected to TVC, the patterning behaviour of the fluid becomes dependent on not only the magnitude of the imposed temperature gradient but also on the frequency and amplitude of the considered vibrations and the direction of these with respect to the temperature gradient

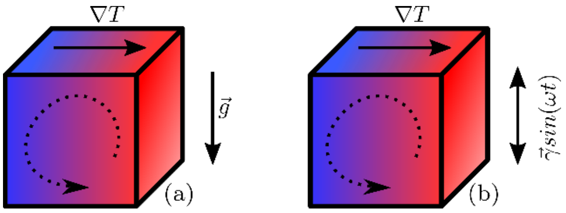

Figure 1: Mathematical model for (a) thermogravitational convection and (b) thermovibrational convection.

When particles are added to the mix, in microgravity conditions (where the only driving force present is due to vibrations), many different patterning behaviours are possible when the space of parameters of TVC is explored (frequency and amplitude of the vibrations). The properties of the particles also contribute to the structure formations, where both the size, density and concentration of particles affect the final structures. An example of possible patterning configurations is depicted in Figure 2 (adapted from Ref [7]).

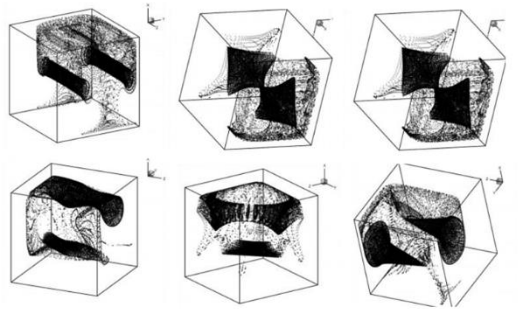

Figure 2: Example of particle aggregate structures varying in shape due to varying different thermo-vibrational conditions.

To keep the ISS experiment as simple as possible and owing to the fact that the project utilises the existing ISS hardware Selectable Optical Diagnostics Instrument (SODI) in combination with the Microgravity Science Glovebox (MSG), only the vibrational frequency, amplitude and temperature difference across the cavity are varied and the direction of vibrations is set in a perpendicular manner to the temperature gradient (as shown in Figure 1).

However, keeping with the aim of expanding the project scope, the involved PhD students (first and second author of the present paper, hereafter simply referred to as GC and AB, respectively) have also considered situations in which the temperature gradient has a different orientation and/or the liquid also possesses elastic properties (non-Newtonian fluids).

2.2. Team composition

A notable aspect of the project is the composition of the team responsible for the successful completion and continuation of the Particle Vibration project. The team is composed of two sub-teams. The science team (based at the University of Strathclyde) includes the principal investigator (fourth author, ML), a research associate (third author, MK) and the two aforementioned PhD students. The team is responsible for providing the exact scientific requirements for the series of experiments to be conducted on board the ISS and for expanding the project scope by pushing its boundaries further. The technical team includes the relevant personnel of the company in charge of manufacturing the experiment hardware (QinetiQ), the ESA project coordinator, the ESA Payload Integration Manager and the User Support and Operations Centre (E-USOC) in charge of commanding remotely the payload and developing the related procedures. In Figure 3 we schematise the composition of both teams.

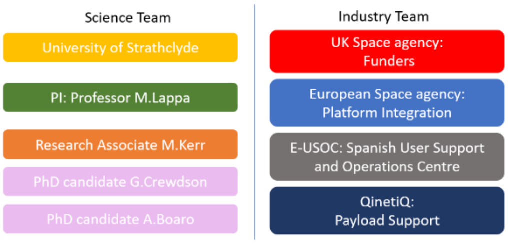

Figure 3: **Composition of the Science and the Industry team.**

3. Discussion

3.1. Project activities and team integration

In this section the various activities undertaken by GC and AB, and directly related to the T-PAOLA space experiment, are discussed.

3.1.1. Experimental activities (GC)

We begin this section with discussing the plethora of experimental activities undertaken GC. For brevity we focus on the two most relevant tasks. Firstly, GC attended a weeklong activity where QinetiQ had been contracted to carry out the “cell filling procedure”, where the quartz cells to be used on the ISS are filled with both the fluid and the particles. During the filling procedure, many foreseen (and unforeseen) obstacles where tackled. These obstacles provided an insight into the difficulty of monitoring and performing the high-precision tasks required for the success of the experiment. The second critical experimental procedure to be carried out was the degassing of the fluid in preparation for the experiment (shown in Figure 4), which was supervised by MK. The related rationale/challenges can be described as follows.

Under atmospheric pressure a small amount of “air” is trapped in the fluid. When the fluid is placed under vacuum, this air is forced out of the fluid creating unwanted air bubbles in the fluid cell. Of course, this can make any particle formations impossible, therefore the fluid must be purged of all residual air before it is inserted in the cell with the particles. This activity involves the use of both compressed gases and liquid nitrogen that required GC taking short courses, hence developing her skill set, as well as contributing to developing bespoke experimental protocols.

Figure 4: Nitrogen gas is bubbled through the ethanol to displace any remaining oxygen.

3.1.2. Data downlink and post processing (AB)

In addition to the fundamental experimental activities, another crucial part of the project has been the treatment of the experimental data (signals and images) produced initially during ground testing. A proper description of these aspects requires the introduction of some details about the control parameters of the experiment (as developed in the following).

As stated in the introduction, TVC arises inside a differentially heated cavity when vibrations are applied. After selecting the properties of the fluid and the particles, four other control parameters remain, namely, the temperature at the top and bottom of the cell, the frequency of the vibrations and their amplitude. In addition, the applied temperature has to be varied sinusoidally in certain stages of the experiment in order to re-disperse the particles (after particle structures are formed for a given combination of the parameters, initial conditions with a uniform distribution of particles must be established for the execution of the next experiment dealing with a different combination of them).

In Autumn 2021 ground tests were carried out by the aforementioned E-USOC with two-fold purpose to 1) assess the consistency of the payload software (experiment “scripts”) with the specifications provided by the scientific team and 2) verify the ability of the hardware to support adequately the ranges of temperature and vibrational frequencies specified through such a set of requirements.

Here, the support of AB was fundamental. He developed a robust algorithm capable of automatically checking the results of the tests against the requirements in terms of duration of every step and amplitude and frequency of both vibrations and temperature. Moreover, the algorithm was also able to classify the pictures recorded during each run and split them into different subgroups according to the specific step of the experiment in which they had been generated. As an example, Figure 5 shows part the algorithm output for a generic run.

This procedure revealed an inconsistency between the image numbering and the recorded signals, which was timely communicated to the E-USOC and fixed accordingly. Moreover, the processed data proved that the hardware could maintain the required thermal modulations.

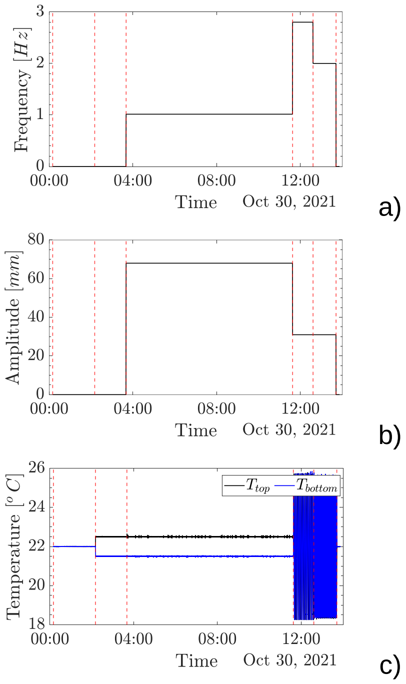

Figure 5: Output of the algorithm. The vertical dashed lines indicate the start of a new step. a) Frequency and b) Amplitude of the vibrations, and c) temperature of the primary cell.

3.2. Expansion of project scope through peripheral research

We now turn to the specific topics of the students PhD theses and show how their activities are contributing to the legacy of the Particle Vibration project not only from a technical point of view, but also in terms of scientific outcomes.

3.2.1. Novel particle control mechanisms (GC)

T-PAOLA focuses on the case where vibrations are perpendicular to the temperature gradient. As part of her PhD GC has also investigated the case where the vibrations are parallel to the temperature gradient. In this case high frequency vibrations tend to "kill" convection therefore limiting the range of parameters that can be explored (as high frequency regimes are therefore excluded from the study). Preliminary research has revealed that highly ordered, time dependent particle structures can yet be achieved under TVC if vibrations with moderate frequency are considered, as shown in Figure 6. In addition to the direction of vibrations, the details of the thermal boundary conditions can also be altered to change the behaviour of the TVC and the ensuing particle accumulation structures.

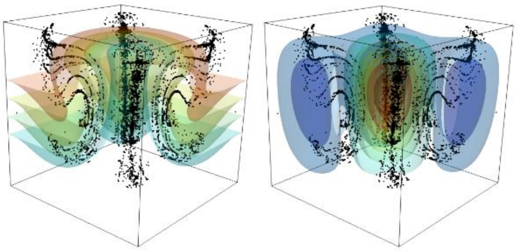

Figure 6: Temperature and velocity fields (left and right respectively), for a 3D cavity seeded with particles where the vibrations are parallel to the temperature gradient.

Figure 7 shows that when the temperature at the top and bottom walls is set in a non-uniform manner and the vibrations are set in the horizontal plane, a plethora of particle structures become possible.

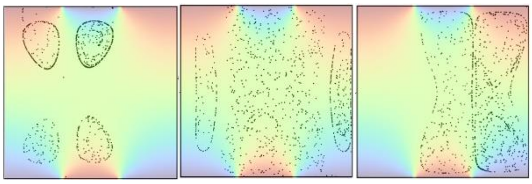

Figure 7: Possbile (2D) particle accumulation structures when a non-uniform heating configuration is considered and vibrations are set in the horizontal plane.The flowfield is colored by temperature.

The variations of structure types seen in Figure 7 are associated with the parameters considered in the study and correspond to a change in the amplitude of the vibrations as well as the size of the particles.

3.2.2. A new line of inquiry: TVC in viscoelastic fluids (AB)

The properties of TVC can also be heavily modified by changing the considered fluid itself. In this regard, AB investigated how TVC manifest itself in a particular class of fluids, i.e., viscoelastic liquids, thereby opening a new path of research. These fluids can exhibit complex states for relatively low values of the imposed temperature difference in comparison to their Newtonian counterparts. Figure 8 shows how these two classes of fluids can exhibit different behaviours even if a problem as simple as a two-dimensional square cavity is considered.

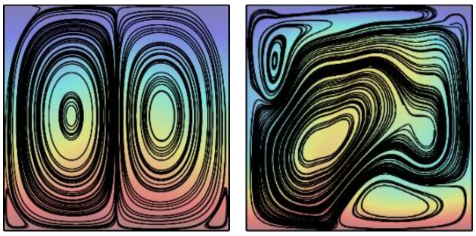

Figure 8: 2D TVC with vibrations parallel to the temperature gradient with Newtonian (left) and viscoelastic (right) fluid. Streamlines and flowfield colored by temperature.

In addition to this classical problem, an infinite layer with vertical vibrations has also been tackled. It has been shown that, like the companion 2D case, the viscoelasticity of the fluid allows the formation of flow patterns that cannot arise in Newtonian fluids in microgravity conditions. As an example, Figure 9 depicts two possible convective states showing well-ordered structures formed under the effect of sinusoidal (as in the T-PAOLA experiment) or square wave vibrations in a viscoelastic liquid.

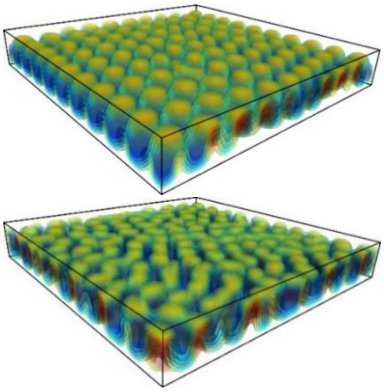

Figure 9: 3D viscoelastic TVC with sinusoidal (top) and square wave (bottom) vibrations. Isosurfaces of the temperature colored by the vertical component of the velocity.

The fascinating patterns just presented, along with the complex dynamic of viscoelastic fluids, make this category of liquid the perfect candidate for future experimental investigations with dispersed solid particles in microgravity conditions. An extensive discussion of the work presented in this section can be found in [6], [8], [9].

3.2.3. Undergraduate student engagement

The T-PAOLA project has also engaged two Bachelor students. Indeed, the results shown in Figure 7 correspond to the work of a bachelor's project student supervised by GC, while the results in Figure 8 relate to another undergraduate project supervised by AB.

4. Conclusions

In conclusion, AB and GC have supported the T-PAOLA project over the last three years. In doing so, the authors have had the opportunity to partake in a real-world space experiment solving a range of problems of both theoretical and practical nature (developing bespoke data treatment algorithms and undertaking complex experimental and numerical simulation work). This has resulted in a mutual exchange of benefits, namely, the successful completion of a number of tasks relevant to the project on the one hand, and the development of a rich variety of PhD student skills and research "attributes", on the other hand. The realization of this "exchange" has involved a fruitful triadic relationship between the PhD students, the supervisor and the many external entities involved in all these processes.

Notably, the numerical work conducted in the frame of the project has also allowed the development of relevant undergraduate students' attributes, namely, the ability to understand the principles of microgravity experimentation and conduct (under the supervision of GC and AB) relevant numerical simulations using available commercial or open-source CFD software. For all these reasons, we recommend involving PhD students in this type of project whenever possible.

Acknowledgements

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