The "Effect of Marangoni convection on heat transfer in Phase Change Materials" experiment, from a student project to the International Space Station

Pablo Salgado Sánchez[1], *Jose Miguel Ezquerro*[2], *Dan Gligor*[2], *Úrsula Martínez*[2], *Jose Fernández*[2], *Ignacio Tinao*[2]

Abstract

This manuscript summarizes the educational and scientific outcome of the Research-based learning activities performed in the bachelor's, master's, and doctorate programmes in aerospace engineering at the Technical University of Madrid. The activities are related to the line of research in Phase Change Materials in microgravity developed at the Spanish User Support and Operations Centre. The principal scientific results obtained during these years are outlined, drawing particular attention to those related to the "Thermocapillary Effects in Phase Change Materials in Microgravity" experiment and the "Effect of Marangoni convection on heat transfer in Phase Change Materials" project. The outcomes of this research are discussed from an educational perspective. Since 2016, we observe an increased interest from students to participate in research activities, which has had direct positive impact on the production of scientific results.

Keywords

Active learning, ISS, Marangoni in PCMs, Microgravity experiments, Research-based learning

[1] Corresponding author: E-USOC, Center for Computational Simulation, Universidad Politécnica de Madrid, Spain, pablo.salgado@upm.es – psalgado@eusoc.upm.es

[2] E-USOC, Center for Computational Simulation, Universidad Politécnica de Madrid, Spain

Acronyms/Abbreviations

B/Md	*Bachelor/Master's degree*
ECTS	*European Credit Transfer System*
ESA	*European Space Agency*
E-USOC	*Spanish User Support and Operations Centre*
ISS	*International Space Station*
MarPCM	*Effect of Marangoni convection on heat transfer in Phase Change Materials*
PCM	*Phase Change Material*
RBL	*Research-based learning*
TEPiM	*Thermocapillary Effects in Phase Change Materials in Microgravity*
UPM	*Universidad Politécnica de Madrid*

1. Introduction

In recent years, universities are evolving toward teaching and learning methods based on active learning [1]. Among these methodologies, challenge-based learning is an excellent example of a widely implemented approach in engineering education, with positive results in the development of generic competencies and soft skills, and in the student's motivation and satisfaction [2],[3]. With a similar educational impact, research-based learning (RBL) [4] aims to connect students with research techniques and methodologies that allow them to develop competencies and analysis, reflection, and argumentation skills.

In the context of RBL, the Spanish User Support and Operations Centre (E-USOC), as part of the Aerospace Science and Operations research group at Universidad Politécnica de Madrid (UPM), has integrated progressively the participation of students in its microgravity research activities, as a way of implementing RBL in tertiary education.

Since its early stages, the line of research in Phase Change Materials (PCMs) and thermal control has counted on with a large student's contribution. Indeed, it was born in 2016 from the student's project "Thermocapillary Effects in Phase Change Materials in microgravity" (TEPiM) [5], and has progressively grown to the point that, a related experiment proposal, is now part of the European Space Agency (ESA) planned experiments that will be executed on board the International Space Station (ISS) in the near future [6].

Motivated in no small part by the worsening environmental problems created by modern society, the use of PCMs as thermal energy storage systems has seized lot of attention in the last few decades. PCMs, characterized by their ability to store and release large amounts of energy in the form of latent heat, are an attractive alternative to improve efficiency and reduce energy waste [7].

Space exploration is a special area of application, for which organic materials like alkanes are a suitable PCM selection, due to their moderate melting temperature and large heat of fusion. Their performance, however, is generally limited by low thermal conductivity. Recently, the thermocapillary effect has been proposed as an enhancement strategy with great potential for microgravity applications [8]. During the phase change, the presence of air or another gas in contact with the liquid phase of the PCM supports thermocapillary convection and provides an additional mechanism for heat transport that improves the performance of the PCM device.

Since 2016, our research activities have focused on the analysis of thermocapillary effects in PCMs in microgravity. The TEPiM experiment furthered our current understanding of PCM melting in microgravity and motivated further efforts. From an experimental research perspective, we highlight the need of microgravity: if thermocapillary convection occurs in a PCM device on ground, it interacts with, or can be even masked, by natural convection, fact that complicates quantifying the contributions of each effect to the heat transfer rate. The final goal is to design more efficient thermal control systems based on PCMs for future space missions.

In this manuscript, we provide an overview of the scientific results and related RBL activities performed. The manuscript is structured as follows. In Sec. 2, a brief review of the TEPiM experiment is given. In Sec. 3, we describe the future "Effect of Marangoni convection on heat transfer in Phase Change Materials" (MarPCM) experiment. In Secs. 4 and 5, the RBL activities performed during these years and associated results are summarized and discussed. Final conclusions are offered in Sec. 6.

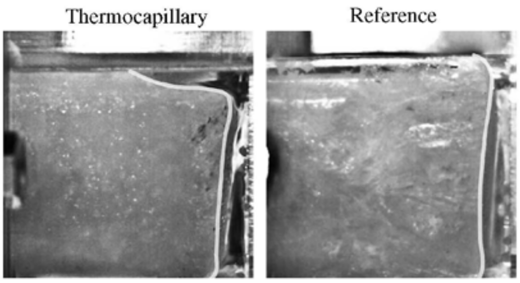

Figure 1. Comparison between thermocapillary and reference cell experiments. Adapted from Ezquerro *et al.* [9].

2. From a student project…: The Thermocapillary Effects in Phase Change Materials in Microgravity experiment

As a first effort to understand the possibility of using the thermocapillary effect as a heat transfer enhancer in microgravity, the research group presented the TEPiM experiment to the call for proposal of the 2016 ESA "Fly your Thesis!" programme, sponsored by the ESA Education Office — the educational division of ESA. The experiment, along with other three projects, was selected [5] to fly onboard the A310 ZERO-G aircraft in the 65th ESA parabolic flight campaign, November 2016.

TEPiM was designed, manufactured, and executed by students, and represents the first set of microgravity experiments on the melting of PCMs with thermocapillary flows.

2.1. The TEPiM experiment

The experiment proposed to study the heat transfer characteristics of PCMs designed with a free surface in reduced gravity. The principal objective was to measure the influence of the associated thermocapillary convection to the solid/liquid phase change [8].

The setup consisted of different pairs of thermocapillary, and reference cells filled with n-octadecane, an organic PCM from the alkanes family. The thermocapillary cells had an air layer on top that supports thermocapillary flows during melting, while the reference counterparts only contained PCM.

Experiments were performed during the repeated microgravity periods of the flight, with an approximate duration of 20 s. During melting, the thermocapillary-driven flow in the liquid phase of the PCM improved the heat transfer rate near the PCM-air interface. The advance of the solid/liquid front was accelerated (locally) in the thermocapillary cells compared to the reference counterparts; see Figure 1 [8],[9].

Overall, TEPiM demonstrated the potential of the thermocapillary effect to enhance heat transport in microgravity [8]–[10] and motivated further research. Note, however, that these results were constrained by the short microgravity timescale of parabolic flights; experiments over larger microgravity periods were needed to definitely evaluate the PCM design and provide data to validate theoretical and numerical models.

3. … to the International Space Station: The Effect of Marangoni convection on heat transfer in Phase Change Materials experiment

Since 2016, we have conducted extensive numerical research [11]–[16]. Results mainly focus on rectangular geometries and n-octadecane. Different studies show that thermocapillary effects depend essentially on container geometry, typified by the aspect ratio Γ, and the applied temperature difference, quantified by the Marangoni number (Ma).

The main conclusions of these works can be outlined as follows:

- Depending on Γ and Ma: (i) heat transport can be enhanced up to a factor of 20 [11], (ii) oscillatory flow can appear [12] in a complex pattern selection scenario [15].
- The performance of the PCM device can be further improved using liquid bridge [14] or trapezoidal [16] geometries.

From an experimental perspective, the MarPCM experiment was recently approved by ESA for its future execution onboard the ISS. This project is the result of a collaboration between UPM, with the E-USOC leading the project, and the universities Mondragon Unibersitatea and Universitat Rovira i Virgili.

3.1. The MarPCM experiment

The experiment will study the effectiveness of thermocapillary flows to improve the heat transfer rate of PCMs and make more efficient use of their energy storage capacity in microgravity. As in TEPiM, the proposed PCM design incorporates a free surface to support thermocapillary convection.

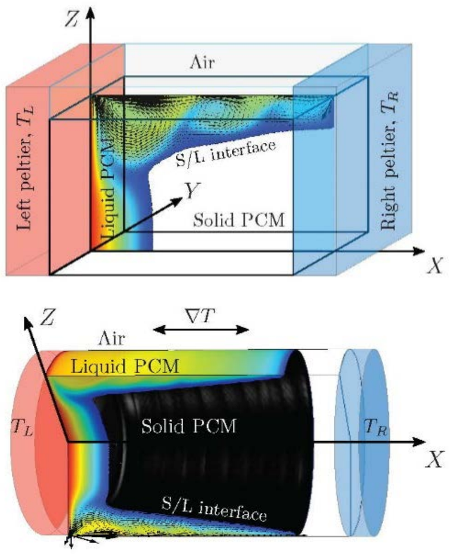

Figure 2. Sketches of the cuboidal and cylindrical (liquid bridge) cells.

Different PCM samples will be subjected to repeated melting/solidification cycles, by applying controlled temperature gradients, and will be held in containers having two different geometries: cuboidal and cylindrical (liquid bridge); see Figure 2. Each of these containers will be designed to passively maintain the PCM/air interface, except for one of the cuboidal cells, which will be filled completely with PCM and will provide a reference measurement of the heat transfer driven solely by conduction.

The phase change evolution will be diagnosed using an optical setup (cameras and illumination) and temperature measurements inside the PCM samples. A quantitative evaluation of the melting/solidification performance between different experiments will be made by comparing the evolution of the solid/liquid interface over time.

Based on simulations, we anticipate that thermocapillary flows will increase the heat transfer rate by a significant factor, depending on the physical properties of the PCM, geometry, and applied temperatures [11]–[14]. Additionally, we expect to observe interesting dynamics related to oscillatory flow. As commented above, different modes can appear [12]–[15], induced by the interaction between the evolving solid/liquid front and the thermocapillary flow.

As will be discussed below, the project has already counted with a large participation of students in different tasks ranging from numerical modelling to the design, manufacturing, and execution of ground experiments.

4. Research-based learning activities and scientific results

At UPM, these research activities are integrated in the curricula of the bachelor's degree (Bd) and master's degree (Md) in aerospace engineering, as well as in the doctorate (PhD) programme in aerospace engineering, as one of the offered lines of research.

At Bd level, RBL is implemented in the context of internships at E-USOC (12 European Credit Transfer System, ECTS) and associated final Bd projects (12 ECTS). Since 2016, 7 projects have been successfully defended, obtaining the maximum grading and excellent evaluations from the tribunals.

At Md level, RBL is analogously introduced as internships (12 ECTS) and associated final Md projects (18 ECTS). Since 2016, 3 projects have been successfully defended with the maximum grading. Currently, another 2 projects related to PCMs are being developed with an expected defence date in July.

At PhD level, 2 theses were recently approved and will be developed in upcoming years. The PhD projects are related to the design and development of the MarPCM ground prototype and associated numerical modelling.

From all these RBL activities, different scientific results have been produced. Since 2016, students have already contributed to 4 oral lectures in 3 international congresses:

- 26th ELGRA Biennial Symposium and General Assembly.
- 71st International Astronautical Congress: Cyberspace Edition.
- 43rd COSPAR Scientific Assembly.

Another 3 abstracts for oral presentations have been recently submitted and are currently under review.

In addition, a total of 9 scientific articles have been published in prestigious journals with the participating students (underlined in the References section) as leading authors in most cases. Another 2 articles have been recently submitted and are currently under review.

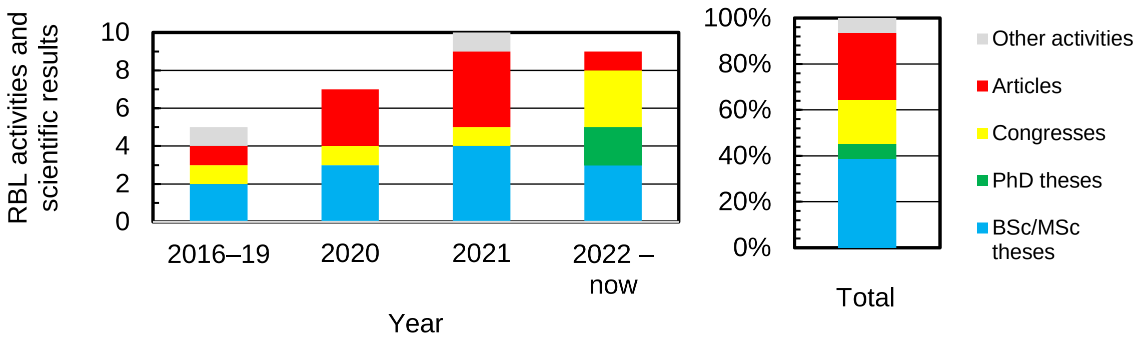

Figure 3. RBL activities and scientific results with student's participation since 2016.

Apart from curricular activities and associated results, we have further participated in other two RBL experiences: the 2019 UPM's science week and the 2021 ESA/ELGRA Gravity-related research summer school [17].

5. Discussion

A summary of the RBL activities and results is illustrated in Figure 3. Since in 2016, there have been an increasing number of activities and associated scientific contributions.

First, one may notice that the total number of final B/Md projects have increased year by year. Each academic course, students showing their interest in doing their projects at E-USOC are put in contact with former students so that they can share their experience. We attribute this increased interest to the overall positive evaluation of the internships at E-USOC.

As a direct consequence, the production of scientific results has grown notably. Since the very beginning of their internships, students are aware of the possibility of publishing their results in prestigious journals, fact that boosts their motivation. In line with this, students usually show their interest in extending their collaboration in subsequent academic years. As a clear example of this, the 2 theses mentioned above are related to PhD candidates who have continued their collaborations since their Bd projects.

From a training perspective, these RBL activities allow the students to integrate into E-USOC activities and participate in a real research experience that extends from the preliminary design of an experiment to its execution. It is not only about learning by doing research from a theoretical perspective, but also about acquiring a global vision of experimental research in microgravity and the complex requirements derived from carrying out experiments in parabolic flights or a unique platform like the ISS.

This experience is very motivating for the students, helping to promote their technological and scientific vocation and to value research in the development of new space technology. In addition, thanks to these activities, students develop transversal skills such as teamwork, oral and written communication in English or time management, among others.

6. Conclusions

This manuscript has summarized the educational and scientific outcomes of the RBL activities performed at E-USOC, within the scope of the Bd, Md and the PhD programmes in aerospace engineering at UPM. The activities are mainly related to the line of research in PCMs in microgravity. The principal scientific results are outlined, drawing particular attention to the TEPiM and MarPCM projects. From an educational perspective, we observe an increased interest from students to participate in research activities, which has had a direct positive impact on the production of scientific results.

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