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The Thermocapillary Effects in Phase Change Materials in Microgravity experiment

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Introduction

By their nature, Phase Change Materials (PCMs) store and release a large amount of energy during phase change, feature that may be put in good use to maintain a system temperature within admissible limits. Such large storage capacity, combined with the thermal stability shown around the melting point, has motivated many industrial applications on ground (Memon, 2014). Space systems, whose operating environment generally results in thermal cycles, have also used PCMs for thermal regulation. Examples of both low and high temperature control systems range from complex engineering applications to daily needs in manned mission (Kim et al. 2013).
Nowadays, a wide variety of PCMs with different working temperatures are available. However, the major disadvantage as thermal control devices, especially in microgravity, is their low thermal conductivity. This leads to long heat storage and discharge phases, reducing their performance. On ground, convection naturally alleviates such constraint, increasing by one order of magnitude the heat transport rate. In microgravity, a fairly well established solution is to place large areas of PCM in contact with high conductive materials (Fernandes et al. 2012). This, however, increases the mass and size of the control devices and, despite of that, it compensates the absence of convection just partially.
We consider here the potential of Marangoni convection for heat transfer enhancement in PCMs in weightless environments. Aiming to measure its influence on the heat transport during the melting process and validate numerical models, the Thermocapillary Effects in Phase Change Materials (TEPiM) experiment was designed. Prior to this project, microgravity experiments of PCMs coupled with thermocapillary convection had not been performed.
The TEPiM experiment was presented to the Fly your Thesis! 2016 programme call for proposals. It was selected to fly in the 65th ESA Parabolic Flight Campaign, November 2016. Throughout the three flights of the campaign, we performed 54 microgravity experiments that explored the melting process varying different experimental parameters. This provided us a perfect starting point to obtain novel experimental data, and gain experience to define and prepare a future sounding rocket or ISS experiment. Here, we describe the scientific objectives and requirements of TEPiM experiment, review the setup and phases, and analyse its performance during the experimental campaign.

Scientific objectives and requirements

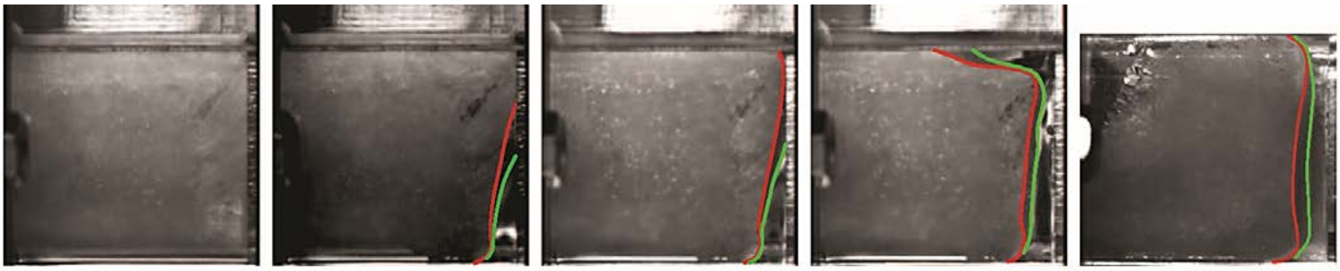
The TEPiM experiment proposed to study PCM dynamics and heat transfer features in the presence of Marangoni convection in microgravity. We note that the presence of a liquid-air interface during PCM melting in microgravity has not been analysed extensively. These studies (see e.g., Giangi et al. 2002, Swanson and Birur 2003) were mostly theoretical.
The two main scientific objectives of this work are:

1. Measure the influence of Marangoni convection in the heat transport process.
2. Retrieve novel experimental data to validate the modelling of the underlying phenomena.

These two objectives require a PCM that displays high latent heat, and a phase change temperature above the ground lab temperature (25 ºC) and below the maximum temperature permitted in the flight (90 ºC). We selected the n-octadecane paraffin as the test PCM.
The experiments were carried onboard an aircraft executing parabolic manoeuvres, providing repeated periods of approximately 20 s of microgravity. Thermally, the typical timescales of Marangoni convection and conductive heat transport for the geometries considered are of tens of seconds and various minutes, respectively. Each experiment required a long preparation phase, dominated by conduction, which helps creating a controlled liquid-air interface at the beginning of a microgravity period. Therefore, the subsequent development of Marangoni convection was essentially concentrated during the 20 s of microgravity, isolating its effects from convection. Each experiment was divided accordingly in: *Preheating* and *Final heating* phases.

The experiment: experimental setup and phases

The heart of the experiment is a set of three pairs of *Marangoni* and *Reference* cells of 20, 25 and 30 mm height, filled with n-octadecane. While the *Reference* cells only contains PCM, the *Marangoni* cells have a 5 mm air layer on top that permits the development of Marangoni convection during melting. Both *Marangoni* and *Reference* cells were subjected to similar thermal loads in the (so-called) Monitoring stations.
During the *Preheating phase*, starting roughly 8 min prior to the relevant microgravity period, the test cell was subjected to 0 ºC and 80 ºC temperatures in its upper and lower sides, respectively. This drove the formation of a liquid paraffin bubble surrounded by solid octadecane [see Fig 1 (a,b)], and prevented the liquid to wet the cell interior filled with air. Around 40 seconds before the microgravity period, the *Final heating* phase started and the cell was subjected to 80ºC at both upper and lower sides.



(a) *Preheating* start (b) *Preheating* end (c) *Final heating* - bridge melting (d) *Final heating* end — *Marangoni* cell (e) *Final heating* end — *Reference* cell

Figure 1: (a-d) Snapshots showing the temporal evolution (times and phases labelled) of an experiment using a *Marangoni* cell. (e) Final snapshot of a *Reference* cell experiment. For visual reference, the (approximate) solid/liquid front in the lateral wall (red line) and central plane (green line) are highlighted.

The solid layer (bridge) separating the liquid paraffin from the air was melted [see Fig 1 (c)], creating the liquid-air interface after, roughly, 30 seconds. The convection generated by thermocapillarity in the liquid phase enhanced the heat transport; accelerating the melting process and the motion of the solid/liquid front near the liquid-air interface [see Fig 1 (d)]. During these reduced gravity periods, we controlled the liquid (phase) dynamics by pinning its contact line, which permits preserving a (nearly-)flat interface. At the experiment completion, the cell was cooled down and the Monitoring station prepared for the following run.

Two cameras, providing lateral and top views; six thermocouples, measuring the experiment temperatures at a maximum rate of 5 Hz in relevant locations; one thermometer, to check the cabin temperature and avoid surpassing the melting point; and the airplane accelerometers, monitored each melting process. For the camera acquisitions, particularly, different sampling rates of approximately 1 Hz for the *Preheating* phase and 10 Hz for the *Final heating* phase were selected.

Given the experiments duration of roughly 10 minutes, we operated two Monitoring stations in parallel to maximise the experiment outcome. This permitted using three microgravity lapses of each group of five parabolas, and thus resulted in a daily set of eighteen microgravity experiments.

Conclusions: preliminary results and lessons learned

Although not all the executed experiments provided the expected results, the TEPiM experiment was successful in many ways. The main preliminary results and lessons learned are as follows:

(i) As shown in Fig. 1 (d, e), the effect of Marangoni convection can be clearly observed in the region near the liquid-air interface, where a greater advance of the solid/liquid front is achieved. Besides that, the processing of these experiments reveals a heat transfer enhancement of, roughly, a factor of 2 between *Marangoni* and *Reference* cells.

(ii) Issues arising from the air retained in the solid PCM suggest that further efforts shall be done to reduce the PCM porosity, e.g., the application of a controlled solidification during the cells filling. PCM porosity further affects the proper observation of experiments, as the optical behaviour of the liquid was altered somewhat during microgravity, potentially, due to the presence of microbubbles.

(iii) The contact line pinning performed excellently. It permitted to maintain the liquid-air interface in all but three experiments throughout the campaign.

(iv) We designed a high performance Thermal Control System. It achieved temperature differences of ~80 ºC in the cells, and was capable to nullify these offsets in a very short time (~30 s), while maintaining high temperatures (~80 ºC).

In light of the above considerations, the TEPiM experiment has shown the potential of Marangoni convection for enhancing heat transport in PCMs in microgravity, providing an alternative to develop more efficient thermal control devices in future space missions.

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