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Gravitational and Space Research

Constrained Vapor Bubble Experiment (CVB) in the Light Microscopy Module (LMM)

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Abstract

This short article describes the major findings from the CVB experiment performed in the LMM on the International Space Station from 2010-2012. CVB was the first experiment to run in the new facility and focused on understanding the heat transfer and fluid mechanics occurring inside a wickless miniature heat pipe. The LMM was used to map the location of the vapor-liquid interface inside the device and to measure the film thickness profile on the walls of the device. Several interesting and unexpected phenomena were observed in microgravity including flooding of the heater end with liquid as the heat input increased, explosive nucleation of vapor bubbles at the heater end in the shortest version of the heat pipe tested, condensation on highly superheated surfaces, and the spontaneous formation of rip currents as the device tried to enhance the contact line area available for evaporation of the liquid.

Keywords

Heat pipe • Interfacial Phenomena • Marangoni Force

Importance of Research on Space Station

The two forces that control capillary-driven heat pipes are gravity and intermolecular/interfacial forces. Since gravity is minimized on the Space Station, the role of intermolecular forces can be more effectively studied in detail. This was accomplished in the unique Constrained Vapor Bubble (CVB) Heat Pipe experiments conducted on the Space Station between 2010 - 2012. CVB was the first experiment to run in the LMM and Fluids Integrated Rack (FIR).

The CVB experiment was the simplest of linear heat pipes, a vapor bubble constrained by transparent glass walls. It was made from a standard, rectangular spectrophotometer cell. An electrical resistance heater was attached to provide the heat input for the evaporator end. At the condenser end, the temperature was held constant by a cold finger and a bank of thermoelectric coolers. Thermocouples were installed along the cuvette to provide a temperature profile. The transparent walls of this heat pipe allowed us to map the location of the liquid-vapor interface and to study the fluid dynamics using optical interferometry. A schematic of a CVB module that fits into the LMM and an image of what the CVB looked like within the microscope are shown in Figure 1. Several versions of the CVB were flown. Three versions of lengths 20, 30, and 40 mm used pentane as the working fluid; one module contained no fluid to assess heat losses solely driven by conduction and radiation, and the fourth, a 30 mm version, used a 94% pentane-6% isohexane mixture. The mixture served as the simplest form of a self-rewetting, working fluid. All the liquids were chosen to perfectly wet or spontaneously spread over the glass surfaces.

Many Surprises

In the microgravity environment on the International Space Station, the two main interfacial forces governing fluid flow inside a wickless heat pipe are the capillary and Marangoni forces. The geometry of the heat pipe defines the capillary force that drives the liquid from the condenser to the evaporator. When the capillary pumping force is not large enough to keep pace with the rate of liquid evaporation, the evaporator end of the heat pipe begins to dry out. This is the most common performance limitation, called the “capillary limit” of a heat pipe. It is the first limitation usually encountered experimentally. The Marangoni force causes liquid to flow in response to a change in its surface tension. In a heat pipe filled with a pure fluid, the Marangoni force drives the liquid from the evaporator end, where the surface tension is lower, toward the condenser end, where the surface tension is higher. Since temperature gradients are highest at the evaporator end,

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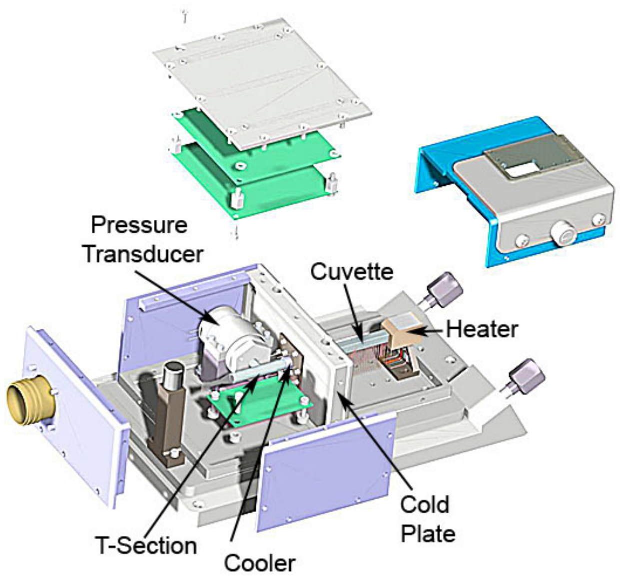
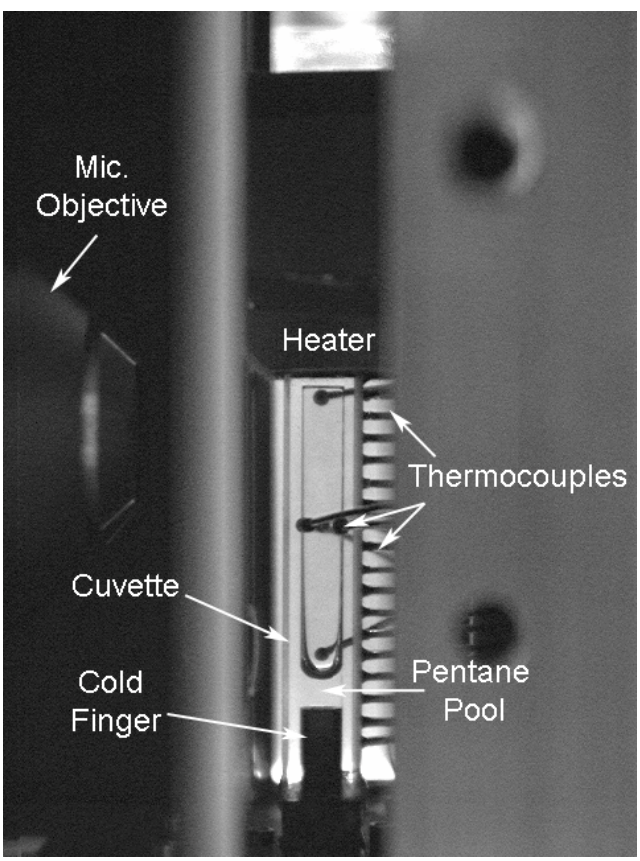


(a)



(b)

Figure 1. (a). Schematic of the CVB assembly that fit into the LMM. (b) Surveillance image of filled CVB module inside the LMM.

changes in surface tension and the Marangoni force there are large. This phenomenon also starves the evaporator end of liquid and can cause the evaporator to dry out even before the “capillary limit” is reached.

Many different groups have reported on the “capillary limit” in their terrestrial experiments. However, the CVB experiment was the first to visualize the vapor-liquid interface in a complete heat pipe in microgravity where natural convection is absent. We found that for those pipes where we used a pure working fluid, as we increased the heat input or decreased the condenser temperature, we accumulated more and more liquid at the heater end (Kundan et al., 2015; Yu et al., 2021). This flooding became more pronounced as the heat pipe length decreased until, for the shortest version, Marangoni forces prevented the vapor bubble from reaching heater end entirely. Here, we observed single, violent nucleation events whose frequency increased as the heater power increased (Plawsky and Warner, 2012; Nguyen et al., 2016). In a way, we achieved controlled boiling. Adding just 6% of a higher boiling point and higher surface tension fluid to the mixture broke this cycle by enabling a composition-driven Marangoni force due to differential evaporation of the liquids to oppose the temperature-driven Marangoni force (Nguyễn et al., 2016; Yu et al., 2022).

The Second Surprise: Condensation Where Only Evaporation Should Have Been Possible

We were able to sustain extremely large superheats at the heater end without drying out. Visual and thermal analyses showed that the culprit was condensation, as indicated in Figure 2 (Kundan et al., 2017). A combination of Marangoni and intermolecular forces caused the liquid film to become unstable at the heater. These forces allowed condensation to occur in the film, which periodically developed a very high curvature and whose adsorbed film thickness dipped below its equilibrium value. To sustain such high heat loads, the evaporation of liquid from the heater wall and four corners of the device was not enough. Thus, the device started to make its own geometry and sent out a jet of fluid toward the heater end. This jet, also evident in Figure 2, was the analog of a rip current at the beach and evaporation from the jet edges served to provide more surface area for change-of-phase heat transfer (Nguyen et al., 2020).

Ongoing Interest

The results from the CVB experiment generated additional interest from the research community, exploring why the system

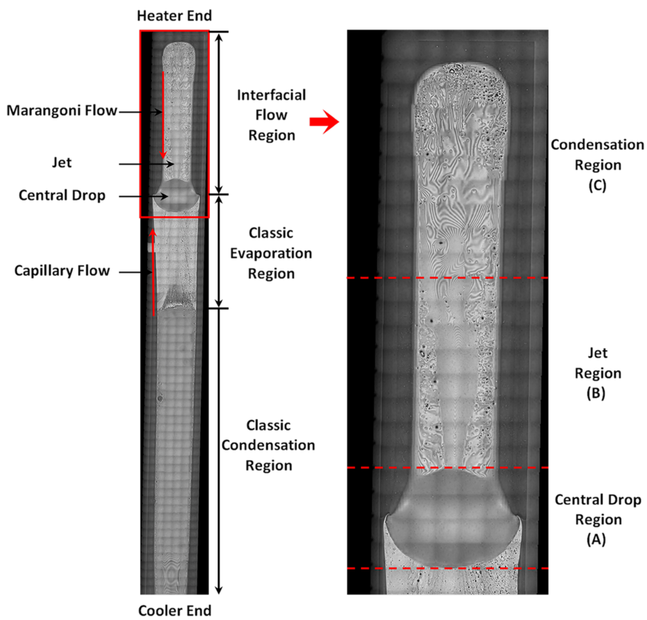


Figure 2. Composite image of the vapor-liquid interface in the CVB. Over 500 separate images taken using the LMM were stitched together. The composite shows the regions of the CVB, the condensation at the heater end, and the rip current formed when the geometry of the device could not sustain the evaporation rate on its own.

behaved the way it did and using the large amount of detailed data obtained to further understand the nature of evaporative heat transfer. As one of the first experiments to have its raw and partially analyzed data loaded into NASA's Physical Sciences Informatics Database, several proposals were funded by NASA to mine that data further (80NSSC18K0332, 80NSSC19K0160, 80NSSC20K0120). Work to expand on the original experiments and study the performance of a 50:50 pentane/isohexane mixture was funded by the NSF/CASIS program (CBET-1637816). The experimental operations on the ISS for the NSF/CASIS experiment concluded in September 2023. In addition, the CVB configuration was used as a vehicle to obtain very precise measurements of the surface tension of mixtures. These follow-on projects have resulted in publications focused on the Marangoni-driven fluid mechanics (Chakrabarti et al., 2023) and the process and universality of the nucleation phenomena (Barrett and Ajax, 2020). Lastly, the experiment is highlighted as part of the LMM exhibit at the Great Lakes Science Center in Cleveland, Ohio. This exhibit is shown in Figure 3, and its purpose is to reach a wide audience and promote interest in space technology.

The CVB showed that fluid dynamics in the simplest of heat pipes can be far more complicated than folks originally believed, especially in microgravity where the stabilizing and performance limiting effects of gravity are missing.

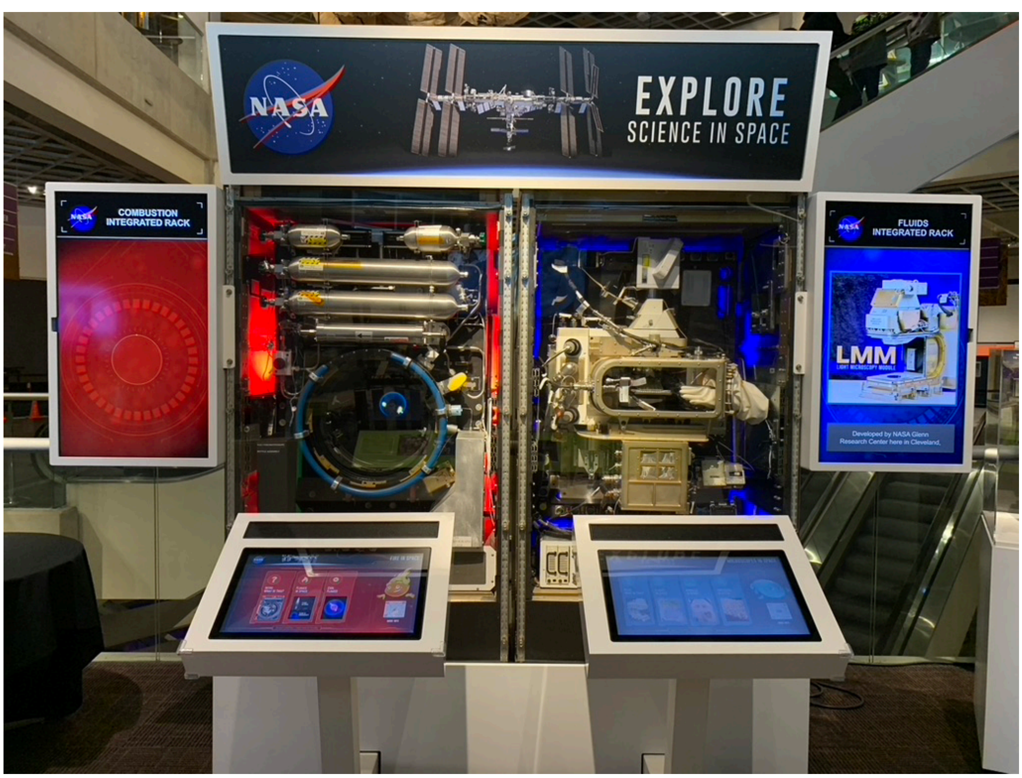


Figure 3. Exhibit on the LMM at the Great Lakes Science Center in Cleveland. CVB is one of the experiments highlighted within the LMM exhibit portion on the right.

Author Disclosure Statement

No competing financial interests exist.

Additional Resources

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