Constrained Vapor Bubble (CVB)

The thermophysical principles underlying change-of-phase heat transfer systems are not well understood in microgravity conditions and are less than optimized even in earth gravity. This experiment proposes basic experimental and theoretical studies of the nonisothermal Constrained Vapor Bubble (CVB) under microgravity conditions. The CVB represents a passive, wickless heat pipe ideally suited to obtain engineering and fundamental data on phase change heat transfer driven by interfacial phenomena. The proposed study represents a basic scientific study in interfacial phenomena, microgravity fluid physics and thermodynamics, a basic study in thermal transport and an engineering study of a passive heat exchanger. This optical study of vapor bubbles constrained in transparent glass cells at variable temperature increases the basic understanding of heat and mass transfer at phase-change interfaces. The information obtained from the study optimizes the design and operation of passive heat transfer devices for earth and microgravity environments and is critically important for the successful completion of long-term lunar and Mars missions.

In this experiment, the crewmember determines the pressure and temperature gradients driving flow through the heat-exchanger optically by measuring the shape of the vapor-liquid interface. Due to their sensitivity to gravity and to small temperature and pressure gradients, these transport systems need to be studied under microgravity conditions to obtain some essential, fundamental information.

The engineering objectives are to determine the stability, the fluid flow characteristics, the average heat transfer coefficient in the evaporation region, and the heat conductance of the CVB as a function of the heat flow rate and vapor volume. The experiment aims to determine the detailed characteristics of the transport processes in a curved liquid film.

NASA and ZIN Technologies developed the experimental setup for flight aboard the International Space Station as a part of the Fluids Integrated Rack (FIR). The Light Microscopy Module (LMM) developed as a part of the FIR consists of a completely automated optical microscope performs a variety of experiments. One of the first experiments intended for the LMM is the CVB experiment.

The assembly consists of a quartz cuvette that is closed at one end. The cuvette cavity is 3 mm 3 mm on the inside and is about 30 mm long. The thickness of the cuvette wall is 1.25 mm, making the outside dimension 5.5 mm 5.5 mm. Thermocouples are attached to the outside surface of the quartz cuvette by drilling holes into the surface of the quartz. A heater is attached to supply heat for evaporation of the working fluid at the closed end of the cuvette. The heater is insulated from all sides so that all the electrical heat input goes into the cuvette only. The open end is sealed with a cold finger that is kept at a constant known low temperature and drains the heat away. To measure pressure, a pressure transducer is attached to the assembly. The cold finger has small holes built into it to create a continuous liquid phase in order to transmit the pressure. The crewmember views the inside surface of the cuvette with the microscope. The CVB module is designed in such a way that the entire assembly containing the experiment cuvette, the thermocouple assembly and the pressure transducer makes a module which can be easily inserted into the Light Microscopy Module. The module is mounted on a moveable stage with x, y and z axis motion to bring regions of the cuvette in the field of view of the microscope objective. The x and y stage movement moves the cuvette while the z movement helps in focusing the image. Lastly, the entire LMM can be tilted around its axis so that the cuvette assembly can be oriented perpendicular or horizontal to gravity.

ISS Science for Everyone

Science Objectives for Everyone

Constrained Vapor Bubble (CVB) aims to achieve a better understanding of the physics of evaporation and condensation and how they affect cooling processes in microgravity using a remotely controlled microscope and a small cooling device.

Science Results for Everyone

When electronics generate heat in spacecraft, astronauts can't just open a window to cool things off. This investigation used a wickless heat pipe to better understand how evaporation and condensation affect cooling processes in microgravity. These devices are well-suited to use in space because they contain no moving parts that might need replacement. Researchers observed unanticipated bubble formations, originating at the heater surface and closely followed by an increase of about 10 percent in the overall heat transfer rate. Using these results, researchers developed simple models of bubble formation, which could help develop more efficient microelectronics cooling systems.

Even pipes sweat when things really heat up in microgravity. Researchers saw more condensation when the device surface was superheated, suggesting that small temperature perturbations due to variations in liquid film thickness effectively superheated the vapor, causing condensation. In other words, thickness and temperature disturbances in the liquid film initiated condensation at the heated end and Marangoni stresses (mass transfer along an interface between two fluids) drove that condensed liquid from the center of the heat pipe to its edges, flooding the heated end. These findings further our understanding of thermodynamics in microgravity, important for future space missions (Kundan, 2017).

Applications

Space Applications

CVB has performed ground-based studies in a thermal vacuum chamber to determine the efficiency of the heater and cooler configuration. Large thermal response times that have been experimentally observed in space-based experiments cannot be obtained from these ground-based studies. Space-based experimentation is the only method available to ascertain internal low-gravity fluid mechanics within a heat pipe.

Earth Applications

The project aims to achieve an improved understanding of microscale heat transfer, improved designs for wickless heat pipes, and an increased efficiency in heat transfer devices for cooling critical components. Targeted users are existing microelectronics industry and perhaps military applications. New designs should be able to be developed several months following the analysis and presentation of the results from the experiment.

Operations

Operational Requirements and Protocols

Several different CVB science modules are developed with different lengths (20 mm, 30 mm and 40 mm). A microscope inside LMM images the length of the science module at different heat settings. The images are sent to the earth for analysis.

Publications

The Constrained Vapor Bubble (CVB) experiment is designed to record, for the first time, the complete distribution of vapor and liquid in a heat pipe operated in microgravity and on Earth. This distribution is essential to understanding how heat pipes operate and how to optimize their design. Heat pipes are ideal devices for cooling critical components in microgravity because they require no moving parts to operate; just a heat source and a heat sink. CVB operated aboard the International Space Station over the course of several months in 2010.

An unanticipated nucleate boiling phenomenon was observed in the microgravity environment on International Space Station during operation of the experiment. Surveillance images of constant volume, microgravity boiling dynamics over a 20-hour time period show that nucleation (bubble formation) episodes occurred in a non-periodic but non-random way. Each nucleation event originated at the heater surface and new bubble growth was accompanied by a shock wave that passed through the heat pipe and partially collapsed the original vapor bubble. The maximum heat input to the heat pipe closely followed the timing of the nucleation event. The maximum heat loss, due to thermal radiation from the walls of the device, followed the timing of bubble motion and bubble coalescence. The whole process resulted in about a 10% increase in the overall heat transfer rate. The critical size of the equilibrium, homogeneous bubble nucleus was determined using the data and standard thermodynamic descriptions of boiling to be on the order of 140 nm for a superheat of roughly 42 K. Aided by these results, researchers developed simple models to describe the effect of main bubble location on the nucleation probability in the CVB and to determine the effect of intermolecular forces on the liquid film thickness needed to support nucleate boiling.

As expected, CVB measurements indicate that heat pipe performance is enhanced in microgravity due to the increased capillary flow returning the liquid to the heater end. The heat transfer processes internal to the CVB pipes are very complex in microgravity, much more complex than originally thought or predicted by existing models. Large temperature changes along the hot-cold axis of the pipe establish surface tension driven flows (Marangoni flow) which oppose the return of the liquid to the hot end. These flows are more important in microgravity and led to the discovery of a new limit to heat pipe performance and the first ever observations of surface tension induced flooding of the heater end, a phenomenon not imagined possible in heat pipes. Contrary to expectation, the heater end of the heat pipe could not be dried out in microgravity even at heat inputs one and a half times more than those applied on Earth. The use of a loop heat pipe or multicomponent liquid mixture may overcome the issue involved with the accumulation of a thick liquid layer at the heat source. The CVB experiment also shows that Marangoni and capillary forces lead to dramatic changes in the behavior of a heat pipe as a function of its length. While flooding of the heater end and the inability to dry out the heat pipe is observed in longer heat pipes, the two forces combine to prevent start-up of the heat pipe in the shortest module. Instead, a rare phenomenon, controlled, explosive nucleation is seen.

These results, and how they relate to Marangoni and capillary forces, impact future designs of heat pipes in microscale flow boiling systems for cooling high power electronics in space and on Earth. Precise control and timing of explosive boiling has already proven its use in inkjet printer technology. This behavior can also be used to produce mechanical work such as moving micro membranes. For NASA, long-term storage of rocket propellants in space is one of the key requirements for planetary space exploration missions. Bubble formation and explosive boiling due to localized heat leaks in storage tanks under microgravity over a long period can be a serious and potentially dangerous condition for space-based fuel depots.

A heat pipe, a device used to transport heat over long distances, was operated on the International Space Station (ISS) to understand how microgravity impacted evaporation and condensation. Heat pipes were divided into three zones: the heated end, the cooled end, and an intermediate zone that formed a boundary between the two ends. Methodologically, heat was supplied to the heated end and the cooled end was kept at a constant temperature using a cold finger. A profile of liquid film thickness was also obtained using interferometry. Unlike ground experiments, which show evaporation at the heated end and condensation at the cooled end, this microgravity study showed a thicker film as heat load increased and a transition from evaporation to condensation at the heated end only – even when the surface temperature exceeded the boiling point of 160° K. In other words, there was more condensation in the pipe when the surface was superheated. These results suggest that small perturbations to the temperature in the intermediate zone of the pipe due to variations in film thickness effectively superheated the vapor and caused condensation to occur. That is, the condensation process at the heated end was initiated by thickness and temperature disturbances in the liquid film that wet the surface. The condensed liquid was driven down the main axis from the center of the heat pipe to its edges by strong Marangoni stresses (i.e., the mass transfer along an interface between two fluids) and this led to flooding of the heated end of the device. These findings further our understanding of thermodynamics in microgravity which are important for future space missions to the ISS and Mars(Kundan, 2017).

Results Publications

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Video

This video provides an overview of the Constrained Vapor Bubble (CVB) hardware. The CVB is a glass, square-shaped tube that is partially filled with liquid. The liquid is pumped from the cold end to the hot end of the tube to create a cooling effect. Since the outside of the CVB is transparent, scientists can observe and record how the liquid behaves. The results of the CVB will help develop more efficient air conditioning systems, refrigeration systems, and better cooling processes for microelectronics and server farms.

https://www.youtube.com/embed/Q_2OOBG0NPE

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Constrained Vapor Bubble-2 (CVB-2)

CVB-2 is a continuation of the original CVB investigation, where the goal is the study of thermophysical principles underlying change-of-phase heat transfer systems. In CVB-2 the effect of replacing a pure fluid (100% Pentane used in CVB) with a mixture (94% Pentane and 6% Isohexane in CVB-2) is observed. The study of the mixture will evaluate the effect of a modified liquid/vapor interfacial shear stress on fluid flow towards the zone of evaporation. Most liquids have a surface tension that decreases with increasing temperature. This phenomenon creates a flow in the direction of increasing surface tension, called "Marangoni Flow". The temperature driven Marangoni Flow reduces the effectiveness of a heat pipe like the CVB because it keeps liquid from returning to the hot end. The use of a liquid mixture can mitigate this effect because the change in mixture composition with temperature opposes the change in surface tension with temperature allowing for liquid to keep flowing toward the hot end of the device. This should change the details of the basic evaporation and condensation processes operating in the cell.

The crewmember determines the pressure gradient driving liquid flow through the heat-exchanger optically by measuring the shape of the vapor-liquid interface. Temperature gradients driving the heat flow are measured using a series of thermocouples drilled into the side of the CVB cell. Due to their sensitivity to gravity and to small temperature and pressure gradients, heat pipe transport systems like the CVB need to be studied under microgravity conditions to obtain some essential, fundamental information about their internal fluid recirculation systems operate.

Part of the rationale for the experiment is to understand how mixtures of fluids behave during evaporation/condensation cycles. This has applications in chemical processes like boiling, evaporation, condensation, refrigeration, distillation, and in stripping processes where a volatile toxic compound would need to be removed from say, groundwater. The operation of the CVB-2 device also provides fundamental reference data that people who work on advanced micro- and nano- structured heat exchange surfaces need to benchmark their inventions. There are also applications to space-based and terrestrial heat pipes. All high-performance laptop computers now incorporate heat pipes to keep their processors cool. Most satellite systems also use heat pipes to keep critical components cool. Fluid mixtures have been reported to perform better, allowing heat pipes incorporating them to be smaller and lighter.

In general, there are many devices where overheating (e.g., computers or LED light bulbs) can seriously degrade performance and lifetime and so need perpetual cooling. Since heat pipes use capillary action instead of a mechanical pump to supply the cooling fluid (which evaporates) to the hot region, they are a sophisticated, quiet, light, reliable, and efficient method to transfer the heat from the hot region. The objective of CVB and CVB-2 is to understand the details of the evaporation/condensation/fluid-flow operation of these devices and thereby lead to better designs. Heat pipes are particularly useful in microgravity because they eliminate the need for a mechanical pump, a primary source of failure in most systems. Since the effect of gravity is absent in microgravity, the process by which a heat pipe operates is also simpler on the ISS and easier to study. However, the results of the study would also be applicable on earth. In our studies, we compare the operation of the same device in 1g and microgravity. Thereby, adding to the general usefulness of the results of the study

NASA and ZIN Technologies developed the experimental setup for flight aboard the International Space Station as a part of the Fluids Integrated Rack (FIR). The Light Microscopy Module (LMM) developed as a part of the FIR consists of a completely automated optical microscope performs a variety of experiments.

Science Objectives

Science Objectives for Everyone

Constrained Vapor Bubble-2 (CVB-2) uses a miniature heat pipe and a mixture of two fuels to investigate the physics and engineering of heat transfer systems. The investigation conducts basic research in thermodynamics, including heat transfer and the phenomena that occur at the boundary between two phases of matter. It also studies the effectiveness of heat transfer using the CVB heat pipe, a passive heat transfer system on the International Space Station.

Science Results for Everyone

Chill out! Devices such as computers need constant cooling to perform well. Small, liquid-filled pipes are one way to transfer heat without pumps or fans. Researchers tested mixtures of water and alcohol in heat pipes in space. Results revealed an ideal mixture of pentane and isohexane that transferred more heat than other fluids, and eliminated common problems caused by changes in fluid surface tension and location of bubble formation in the pipe. These insights into how heat transfers in microgravity and how mixtures of fluids behave have applications in space and a variety of industries on Earth.

Applications

Space Applications

Most liquids have a surface tension that decreases as temperature rises. This causes fluid to flow in the direction of higher surface tension, a phenomenon known as Marangoni flow. This reduces the effectiveness of a heat pipe, because liquid cannot return to the hot end. CVB-2 investigates whether a mixture of two fuels (pentane and isohexane) that can reduce Marangoni flow and improve the efficiency of the CVB system on the International Space Station. In addition, the investigation provides insight into how heat transfer functions in microgravity. Most satellites use heat pipes to keep critical parts cool, and improved understanding of fluid mixtures could enable future heat pipes that are smaller, lighter and less expensive to launch.

Earth Applications

A wide range of high-performance devices must be perpetually cooled in order to function, from supercomputers to personal laptops and LED light bulbs. Fluid mixtures circulating through heat pipes can passively dissipate heat, using less energy than fans or cooling systems. But heat pipe transport systems are sensitive to small differences in temperature, pressure, and gravity. Studying how fluid mixtures and heat pipes function in microgravity provides insight into the fundamental principles of thermodynamics. This also provides insight into how mixtures of fluids behave during boiling, condensation, evaporation, distillation, and stripping. These processes are used in a variety of industries and environmental cleanup.

Publications

CVB-2 studied heat transfer systems, using a heat pipe. A heat pipe contains a fluid that moves within it, transferring heat without a pump. Recently, several research groups used fluids containing water and a low concentration of alcohol. This resulted in better performance of the heat pipe. The alcohol/water combinations were peculiar in that for a certain composition range, the surface tension increases with increasing temperature. This caused the liquid to move toward the hotter end of the pipe. For the first time, the team used an ideal fluid mixture of 94 percent-by-volume pentane and 6 percent-by-volume isohexane as the working fluid. Using a simple heat transfer model developed in their laboratory, they determined an internal heat transfer coefficient in the evaporator section. They showed this coefficient to be almost twice that of pure pentane under the same conditions. The Marangoni stress in the mixture was five times lower, which led to less liquid accumulation near the heater end. Images of the device *showed that the bubble gets much closer to the heater end in the mixture case. This differed from the original CVB experiment, when the bubble was isolated from the heater by a thick liquid pool. The proximity of the bubble to the heater wall led to more evaporation at the heater end in the mixture case, and therefore a higher heat transfer coefficient. Experiments with heat pipes provide insight into how mixtures of fluids behave during boiling, condensation, evaporation, distillation, and stripping. A variety of industries, including environmental cleanup, use these processes.*

Results Publications

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