National Aeronautics and Space Administration

A Researcher's Guide to:

INTERNATIONAL SPACE STATION

Fluid Physics

This International Space Station (ISS) Researcher's Guide is published by the NASA ISS Program Science Office.

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Cover and back cover:

Front: *The Zero Boil-Off Tank experiment used perfluoro-n-pentane to simulate a cryogenic propellant to study the pressurization of a volatile fluid as the fluid absorbs heat. Mixing the tank can be used to reduce the pressure. During this particular test, as the fluid was mixed and the pressure dropped, residual heat in the metallic components at the tank exit nucleated smaller bubbles that were circulated in the tank around the large vapor bubble or tank ullage. (Image credit: NASA)*

Back: *The Observation and Analysis of Smectic Islands in Space (OASIS) experiment was conducted aboard the ISS in the Microgravity Science Glovebox. It examined the unique characteristics of freely suspended liquid crystals in a microgravity environment to advance the understanding of two-dimensional hydrodynamics. The image is a microscopic view of the thin film liquid that contains multiple layers of liquid crystals that alter the localized color of the film. Two layers of crystals are black, approximately 10 layers are white, 25 layers are yellow, 50 layers are red and 60 layers are blue. (Image credit: NASA)*

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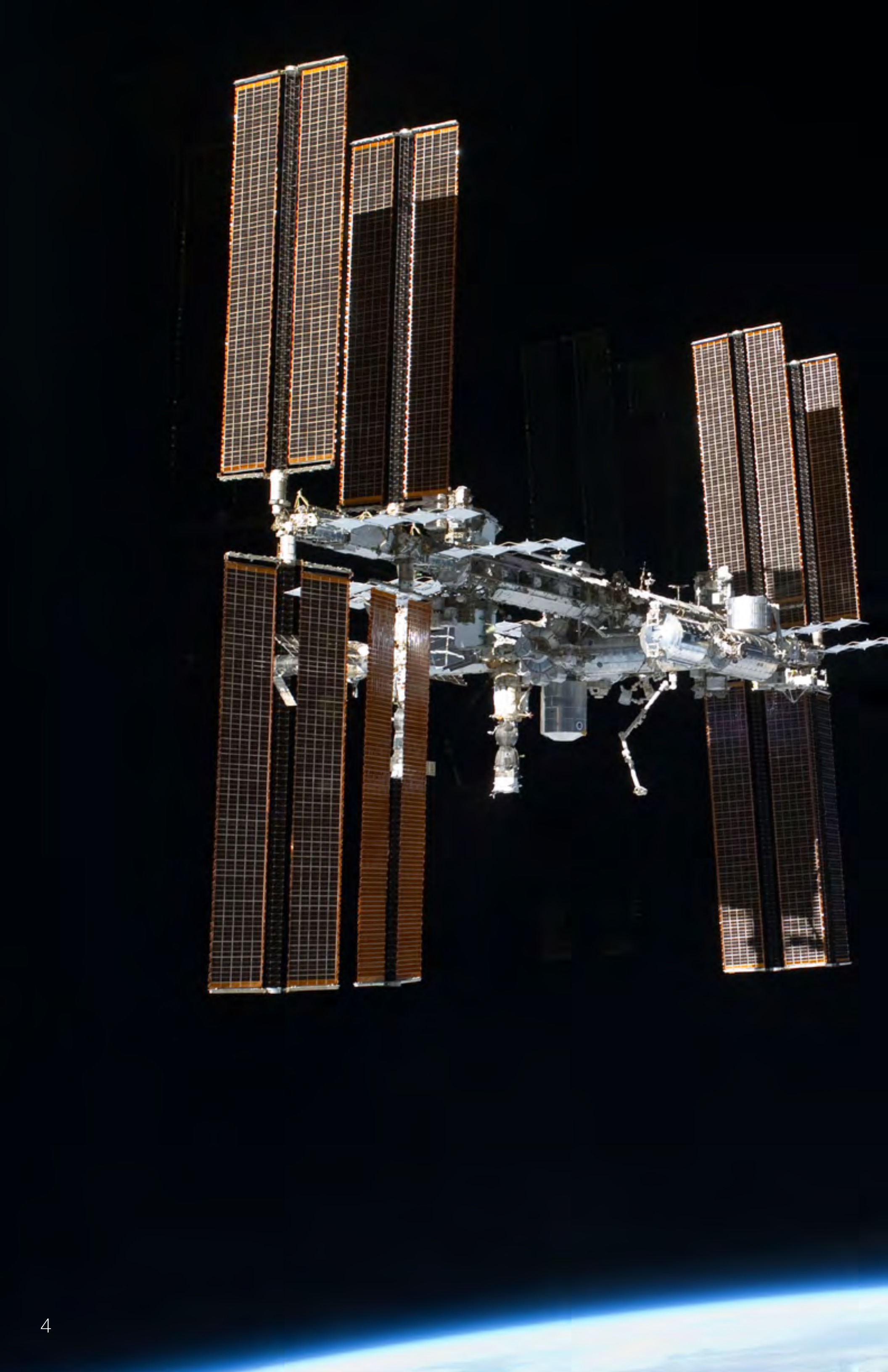
The Lab is Open

Orbiting 250 miles above the Earth, the International Space Station (ISS) provides a platform for research to improve life on Earth, enable space exploration, and understand the universe. The intent of this researcher's guide is to help potential ISS fluid physics researchers plan experiments using the microgravity environment to understand how heat and mass transfer affect fluid flows and behavior. It covers the nature of the acceleration environment on ISS, available facilities for conducting fluid physics research, examples of previous microgravity research, and current fluid physics projects being developed for execution on the ISS.

European Space Agency astronaut Commander Alex Gerst conducts operations to reconfigure the Light Microscopy Module (LMM) from Advanced Colloids Experiment-Temperature-7 (ACE-T-7) experiment operations to Biophysics experiment operations. He is holding a removed ACE Module. (Image credit: NASA)



Unique Features of the ISS Research Environment

1. **Microgravity**, or apparent weightlessness, alters many observable phenomena within the physical and life sciences. Systems and processes affected by microgravity include surface wetting and interfacial tension, multiphase flow and heat transfer, multiphase system dynamics, solidification, and fire phenomena and combustion. Microgravity induces a vast array of changes in organisms ranging from bacteria to humans, including global alterations in gene expression and three-dimensional (3D) aggregation of cells into tissue-like architecture.

2. **Extreme external environmental conditions** imposed on the ISS include exposure to extreme heat and cold cycling, ultra-vacuum, atomic oxygen, and high-energy radiation. Testing and qualification of materials exposed to these extreme conditions have provided data to enable the manufacturing of long-life, reliable components used on Earth as well as in the world's most sophisticated satellite and spacecraft components.

3. **Low-Earth orbit** at 51 degrees orbital inclination and at a 90-minute orbit affords ISS a unique vantage point with an altitude of approximately 250 miles (400 kilometers) and an orbital path over 90 percent of the Earth's population. This orbital path can provide improved spatial resolution and variable lighting conditions compared to the sun-synchronous orbits of typical Earth remote-sensing satellites.

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Why Use the ISS as a Laboratory for Fluid Physics?

A fluid is any material that flows in response to an applied force; thus, both liquids and gases are fluids. Nearly all life support processes, environmental and biological, take place in the fluid phase. Fluid motion accounts for most transport and mixing in both natural and man-made processes as well as within all living organisms. Fluid physics is the study of the motions of liquids and gases and the associated transport of mass, momentum and energy. The need for a better understanding of fluid behavior has created a vigorous, multidisciplinary research community whose ongoing vitality is marked by the continuous emergence of new fields in both basic and applied science. In particular, the low-gravity environment offers a unique opportunity for the study of fluid physics and transport phenomena. The nearly weightless conditions allow researchers to observe and control fluid phenomena in ways that are not possible on Earth.

Experiments conducted in space have yielded rich results. Some outcomes were unexpected and most cannot be observed in Earth-based labs. These results have provided valuable insights into fundamental fluid behavior that apply to both terrestrial and space environments. In addition, research on fluid management and heat transfer for both propulsion and life-support systems has contributed greatly to U.S. leadership in space exploration.

Much is still unknown or not fully understood. In order to design for the human or robotic exploration of space and other planetary environments, it is necessary to understand how engineering and fluid systems perform in the near-weightless environment experienced during space travel or in the reduced-gravity environments found on the moon or Mars.

The differences in the behavior of fluid systems in space or on other planetary bodies can be attributed primarily to buoyancy. The near elimination of buoyancy and sedimentation within inhomogeneous fluids in the low-gravity environment provided by the ISS allows scientists to study the behavior of a whole range of fluids. While these conditions can be achieved in free-fall facilities such as drop towers and aircraft, the limited duration of these tests is insufficient for fluids experiments that require minutes, hours or even days to be performed successfully.

The fluid physics discipline, which focuses on gravity-related research issues, includes the study of complex fluids, multiphase flow and heat transfer, and interfacial phenomena (including capillary flow).

Results from Past Research on Fluid Physics in Space

Gravity strongly affects fluid behavior by creating forces that drive motion, shape, phase boundaries and squeeze gases. One significant gravity-driven motion is buoyancy-induced flow in which lighter, less-dense fluids flow upward while denser fluids flow downward. An example of this type of flow can be found in boiling water in which steam bubbles rise as cooler, and denser water flows down. Sedimentation is a similar gravity-driven phenomenon. In microgravity, the effects of these gravity-driven processes are nearly eliminated. The absence of these phenomena allows scientists to observe other phenomena that are present under the influence of Earth's gravity but are usually obscured.

Complex Fluids

Complex fluids include non-Newtonian fluids such as colloids, polymers, foams, microemulsions, gels, granular materials, and a number of biological materials such as proteins, biomembranes and cells. Complex fluids comprise a large class of materials ranging in size from sub-nanometer to micron scales with their physical properties determined by the interplay of entropic and structural intermolecular forces and interfacial interactions.

Descriptions of sample research into colloids, liquid crystals, and the behavior of smectic bubbles conducted on ISS are provided in the following sections.

Colloids

Prior to the ISS, a series of microgravity experiments were flown that yielded many new and interesting results. Some of the early experiments included Colloidal Disorder-Order Transition, Colloidal Gellation-2, and Physics of Hard Spheres, all flown on the space shuttle.

They revealed the first observations of dendritic growth in hard-sphere colloidal systems. Research results established that colloidal samples remaining in a glassy phase on Earth (i.e., do not crystallize on Earth), become ordered (i.e., crystallize) in microgravity.

On the ISS, the Physics of Colloids in Space (PCS) experiment studied the phase behavior, growth dynamics, morphology and mechanical properties of different types of colloidal suspensions, including binary colloidal alloys (Figure 1), colloidal polymer mixtures, fractal colloidal aggregates, and the natural entropy-driven transition from a disordered glassy state to an ordered crystalline one (Figure 2).

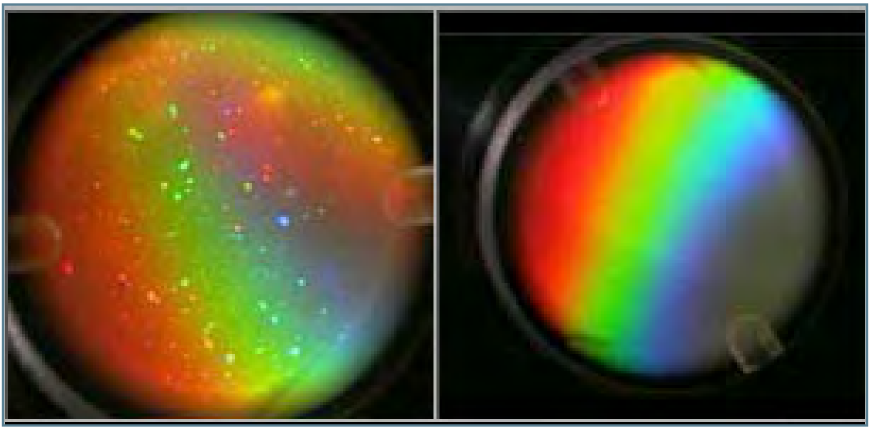


Figure 1. Ground vs. space: The two PCS photos above are of white light shown through binary alloy samples (Manley, et al, 2004). The left sample was grown on the ground and the right sample (sample AB6) was grown on the ISS during Increment 2. The different colors are the result of different wavelengths of light being diffracted by the crystal nuclei, indicating the ordered placement of particles in the suspension. A sharply defined spectrum reveals a highly ordered particle placement in the colloidal suspension

The Binary Colloidal Alloy Tests (BCAT)-3/4/5/6 experiments were a set of notebook-sized science investigations that contained 10 samples each. Once in the microgravity environment aboard the ISS, these samples were individually mixed until their structures were randomized and the samples were photographed as the structures evolved. Many different areas of fluid physics were addressed.

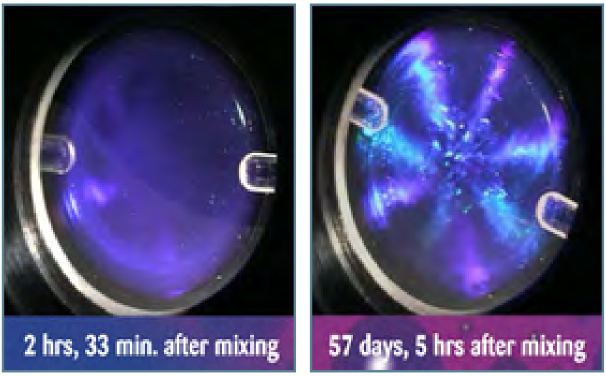


Figure 2. Investigations conducted by Physics of Colloids in Space principal investigators have yielded some unexpected and pleasantly surprising results: solutions that formed glasses on Earth formed crystals and dendritic growth in space; and nucleation and growth that was anticipated by preliminary studies but never observed during the crystal growth process (Cheng, et al., 2002).

The BCAT experiments on seeded growth showed that glassy (completely disordered) samples crystallize differently in the absence of gravitational sedimentation and jamming as shown in Figure 3. The use of seed particles were predicted to cause heterogeneous nucleation (many different crystals) rather than large homogeneous crystals.

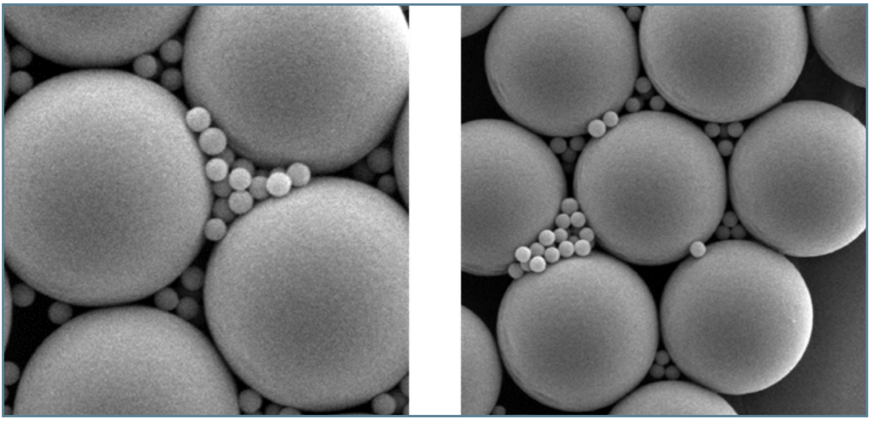


Figure 3. Scanning Electroid Microscope (SEM) images of a mixture of 3.8 micron diameter "seed" particles together with the bulk colloid (0.33 micron diameter polymethyl methacrylate (PMMA) spheres). Crystal nucleation on the spherical surfaces could produce small nuclei that grow radially outward. Because of curvature that makes it difficult to maintain an unstrained structure, they should detach from the surface, allowing the seed to produce new crystal nuclei.

Another focus of the BCAT experiments is the study of phase separation with model-critical fluid samples on the ISS. These model systems do not require the micro-Kelvin temperature control of traditional critical fluids. They serve as a model for understanding ideal systems formed from same-size (monodisperse) particles whose attractive force can be adjusted by the addition of a polymer. Depletion attraction is used to determine the effective attractive force between particles. From these studies, it was found that the critical point is not where the literature predicted (this literature was based on observing phase separation in the presence of gravity). A true microgravity environment is needed to probe these physics.

The competition between a phase-separation process and an order-disorder transition remains largely unstudied. BCAT measurements capturing the arrest of phase separation by crystallization are the focus of the "Complete" Samples. Improved understanding of these processes will lead to more refined manufacturing processes and commercial products. Some exciting and pleasantly surprising results are shown in Figure 4.

Magnetorheological (MR) fluids are suspensions of small (micron-sized) superparamagnetic particles in a nonmagnetic medium. These controllable fluids can quickly transition into a nearly solid-like state when exposed to a magnetic

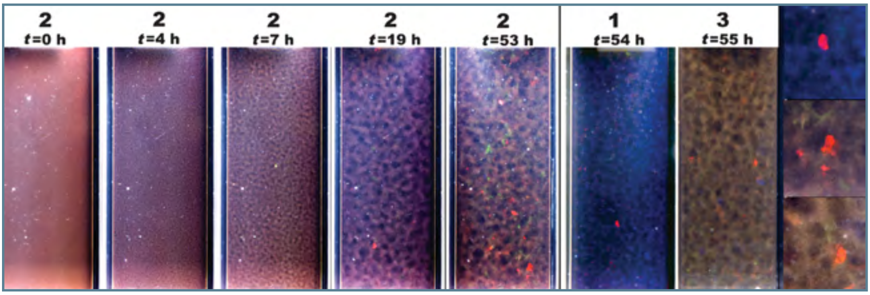


Figure 4. Images of the samples in microgravity. The left five images show sample 2 evolving from time t=0 to t=53 h. Domains in the 19 and 53 h images have exactly the same pattern. Crystal visibility was improved in the 53 h image by an illumination change. The two images to the right show the other two samples at comparable times. Each of these seven images shows the full width of the cuvette. The three images on the far right show a 2.5 mm wide region of each sample with a prominent crystal: sample 1 at the top to sample 3 at the bottom. The crystal size is comparable to the liquid domain size. Figure and caption from Sabin, et al, 2012.

field and return to their original liquid state when the magnetic field is removed. Their rheological properties (how they deform and flow) can be controlled by manipulating the strength of the magnetic field. Because of the rapid response that can be achieved between mechanical components and electronic controls, MR fluids can be used to improve or develop new brake systems, seat suspensions, robotics, clutches, and airplane landing gear.

The Investigating the Structures of Paramagnetic Aggregates from Colloidal Emulsions experiment studied the fundamental behavior of MR fluids under the application of constant and pulsed magnetic fields (Furst, et al., 2011). Observations of the microscopic structures yielded a better understanding of the interplay of magnetic, surface and repulsion forces between structures in these fluids. These fluids are classified as smart materials because they transition to a solid-like state by the formation and cross-linking of microstructures in the presence of a magnetic field. On Earth, these materials are used for vibration dampening systems that can be activated as needed. This technology shows promise for designing structures such as bridges and buildings that can better tolerate earthquake damage.

The Shear History Extensional Rheology Experiment was designed to investigate the effect of preshearing (rotation) on the stress and strain response of a polymer fluid (a complex fluid containing long chains of polymer molecules) being stretched in microgravity (Hall, et al., 2006). This information is particularly relevant for understanding the deformation and evolution of non-Newtonian thin fluid columns (threads) in a wide variety of industrial processes such as fiber spinning, film coating, enhanced oil recovery, injection molding, drag reduction for advanced aircraft, boats and submarines, or food and consumer product processing. In fiber spinning, the fluid experiences a complex transient shear deformation as it flows through the spinneret before it is stretched axially. Additionally, a fundamental understanding and measurement of the extensional rheology of complex fluids is important for understanding the stability and breakup of jets and containerless processing. It is an important operation for fabrication of parts, such as adhesives or fillers, using elastomeric materials on future exploration missions.

In a microgravity environment, there is a large increase in the radial dimension of an initial liquid bridge because of the absence of gravitational body forces. When the initial radius increases, the viscous force is increased and the time evolution of the tensile force becomes slow enough to be measurable for extended times, permitting the long dynamics of the filament thinning to be monitored. A stable microgravity environment enables the understanding of the effect of the initial conditions on capillary thinning and time to breakup.

A 3D confocal capability was added to the Light Microscopy Module (LMM), a microgravity microscope in the Fluids Integrated Rack on the ISS, with sample temperature control. These changes moved microgravity colloids research from the macroscopic to the microscopic, enabling discoveries important for "colloidal engineering," such as the self-assembly of microstructures in a controlled fashion.

One of the first Advanced Colloids Experiments with sample temperature control (ACE-T) to use confocal microscopy studied the behavior of mixtures made from colloids of slightly different sized particles commonly found in commercial products. The study of these polydispersed colloids in ground-based laboratories suffers from their tendency to sediment because of gravity.

In many commercial applications, the manufacturer strives for the formation of a colloidal gel, a connected network of colloidal particles that can stabilize the system against sedimentation. As a colloidal gel, the product is in an arrested state of transition between a fluid and a solid, and the aim of the manufacturer is to keep the product in this state for as long as possible to maximize shelf life.

Matthew Lynch of Procter & Gamble is the Principal Investigator of the ACE-T6 experiment. He discovered that two sizes of stabilizer particles (2.2 micron and 1.8 micron in diameter) behave quite differently in microgravity. The larger particles build scaffolding (product stabilizers) while the smaller particles swarm about the larger particles. The discovery of this behavior is a step toward understanding polydisperse colloidal systems and how polydispersity could affect the stability of colloidal gels.

The science team led by Weitz from Harvard has been able to observe novel behavior with the ACE-M2R experiment, which studied a kinetically arrested gel phase which had never been theorized before (Kodger, et.al., 2017). They were able to measure this kinetic arrest and long-term stability of their sample for 100 million seconds, orders of magnitude longer than similar experiments carried out on earth.

Both of the above experiments should shed insight into the long-term stability of a variety of complex-fluid systems, such as the personal-care products, food and medicines. This insight is being applied on Earth (Proctor and Gamble was awarded four patents) and should improve the shelf life of products needed for long-term human space exploration and habitation beyond low-earth orbit.

The ACE-T1 investigation, led by Chang-Soo Lee from Chungnam National University in Daejeon, South Korea, demonstrated controlling the rotational diffusion coefficient of colloidal particles. The results of this colloidal engineering study of has an emphasis on self-assembly, used to form precisely organized structures spontaneously by thermodynamic equilibrium. The complex structures that result from self-assembly at the molecular level are regulated by highly specific and directional interactions. The ACE-T1 experiment found that the 3D rotational Brownian motion of anisotropic particles can be controlled by choosing the amount of their surface that is hydrophobic. The study of the Brownian motion of anisotropic particles provided insights important for the following topics: (1) equilibrium and non-equilibrium statistical physics, (2) biophysics, (3) soft matter, (4) artificial Brownian motor, (5) micro-rheology, (6) micro robotics, (8) self-assembly of anisotropic particles, and (8) anisotropic molecules in membranes.

The ACE-T7 investigation, led by Prof. Paul Chaikin of New York University, observed 3D formations of “super-cubes” that self-organize into crystalline structures. This ability to design functional structures based on micron-scale building blocks with a variety of well-controlled 3D bonding symmetries will enable the development of new devices for chemical energy, communication, and photonics, including photonic materials to control and manipulate light. This capability underpins the rapidly growing fields of 3D printing and additive manufacturing that rely on the assembly and sintering of particle aggregates as well as the preparation of high-density slurries and pastes of different colloidal materials with different rheological and mechanical properties.

Liquid Crystals

Smectic liquid crystals are composed of fluid layers that can be made to form freely suspended, single component fluid films as thin as a single molecular layer (3 nm). They are the thinnest known stable fluid structures and have the largest surface-to-volume ratio of any fluid concoction, making them ideal for the study of two-dimensional phase transitions, fluid flow, and fluctuation and interface phenomena. They offer unique opportunities to use microgravity effectively to extend the study of basic capillary phenomena to ultrathin fluid films.

Smectic layering forces films to be an integral number of layers thick and to be physically homogeneous with respect to the layer structure over the entire area. This fluid-layer structure and the low vapor pressure of smectics stabilize the freely suspended, single component fluid film for detailed study.

The Observation and Analysis of Smectic Islands in Space (OASIS) experiments, led by Prof. Noel Clark from the University of Colorado at Boulder, focused on using a novel collective system of interacting one-dimensional interfaces in two-dimensional fluids (Clark et al, 2017). This system was ideal for studying fundamental fluid physics such as collective molecular ordering, defect and fluctuation phenomena, hydrodynamics, and nonequilibrium behavior in two dimensions (2D), including serving as models of complex biological membranes. Smectic films were prepared as bubbles supported on an inflation tube. The dynamics of emulsions of smectic islands (thicker regions on thin background films) and of microdroplet inclusions in spherical films, as well as thermocapillary effects, were studied over extended periods within the OASIS (Stannarius, et al., 2019). The technical details of the OASIS hardware and preliminary observations are presented below.

Plateau-Rayleigh Instability

A two-dimensional equivalent of the Plateau-Rayleigh instability was observed in a thin bubble of smectic A (SmA) liquid crystal. In this experiment, a thin bubble was created and the temperature was raised locally to approximately 35^{o}C using a heated needle located near the "north pole" of the bubble. A gentle stream of air was applied across the top of the bubble, causing flow within the bubble film that eventually dragged residual material originally located near the inflation needle into a continuous ribbon of thicker material in the flow direction and around the bubble as shown in Figure 5. This steady-state motion of the ribbon could be continued indefinitely.

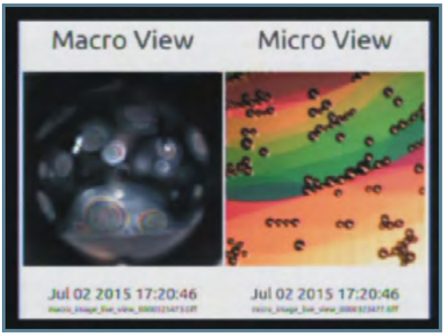


Figure 5: Plateau-Rayleigh Instability: the line tension (the two-dimensional equivalent of surface tension) becomes unstable to small shape perturbations and pinches off into islands.

However, when the heater needle temperature was increased to 45ºC, a dramatic transition in the shape of the liquid ribbon occurred, with the ribbon breaking into a chain of small disks (the two-dimensional equivalent of droplets), which then continued to flow around the film. It is theorized that this increase in temperature sufficiently lowered the line tension (the two-dimensional equivalent of surface tension) of the ribbon so that it became unstable to small shape perturbations and pinched off into islands, similar to the behavior of a water jet in three dimensions.

Island Emulsion Coarsening

Air jets were used to create extensional flow in an initially homogeneously thin bubble film. The air flow broke the thicker material into small, disk-like inclusions called islands that then formed a 2D emulsion on the bubble surface shown in Figure 6.

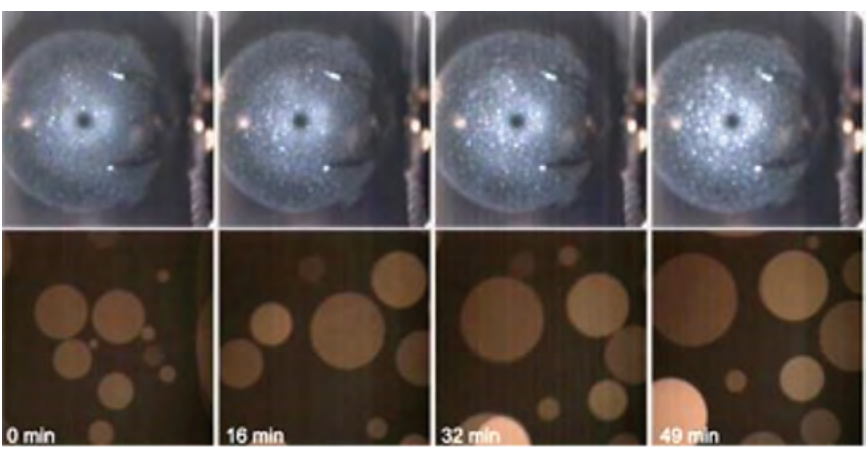


Figure 6: The coarsening dynamics of island emulsions on the two-dimensional surface of bubbles of smectic liquid crystal.

On Earth, such island emulsions would rapidly sediment to the lowest point of the bubble and coalesce; but in microgravity, coarsening of the emulsion was observed free of gravitational effects. Early observations of 15 mm diameter smectic A liquid crystal bubbles confirm that an emulsion of small islands evolves to a significantly coarser ensemble of islands within about one hour. Much of the coarsening appears to be the result of island coalescence events.

Ostwald Ripening and Collapse of Islands in Smectic Bubble

The Ostwald ripening of essentially 2D smectic A and C islands occurs as a result of the system's tendency to reduce its energy through a decrease in the total length of the boundaries of the islands. This process is generally dependent on the (thickness-dependent) surface and line tension, the disjoining pressure of the island, and the excess air pressure inside the bubble. Smaller islands generally have a higher disjoining pressure than their larger neighbors, resulting in permeative flow from the smaller to the larger islands. In smectic bubbles, pressure in the films is mainly determined not by the meniscus, but instead by the excess pressure in the bubble, inducing a change in the physics of collapse and ripening of islands in smectic films.

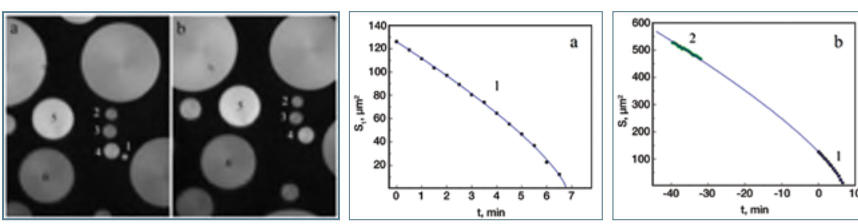


Figure 7: ISLANDS IN A SmC BUBBLE:
(a) Time dependence of area of the smallest island in upper left image (Island 1). The island collapses and disappears. The solid curve is the fit of the experiment data by a power law dependence $S=A(t0-t)^{\beta}$. For the exponent β, the fit gives a value of 0.749±0.02.
(b) Area of the two smallest islands in the images (Islands 1 and 2) as a function of time. The solid curve is the same power dependence as in (a) plotted in a wide temporal range. The experiment data for Island 2 are shifted along the horizontal axis to the theoretical curve. The experiment data for both islands can be described by the same dependence (the slope of the dependence S(t) for Island 2 is close to the slope of the theoretical curve).

Figure 7 shows images of islands in a SmC bubble. The photograph (b) was taken 7.5 min after photograph (a). The behavior of islands 1-6 is different: island 1 disappears in image b while an increase of size of the remaining islands is observed. This behavior is a manifestation of Ostwald ripening. The change of size of islands with time is shown in detail in Figure 7a and Figure 7b. The horizontal size of the images is 335 µm.

Time and Space Periodic Structures of Isotropic Inclusions (Droplets) on Smectic Bubbles

Collective behavior of isotropic droplets dispersed over a spherical smectic bubble was studied in microgravity conditions. Droplets can form two-dimensional hexagonal structures. The one-dimensional motion of droplets with non-uniform velocity demonstrated a peculiar periodic in time ordering of the droplets. This behavior can be considered a classical analogue of discrete "time crystal." The concept of time crystals was put forward by Frank Wilczek. The essential feature of a time crystal is that it restores the same state at specific moments of time.

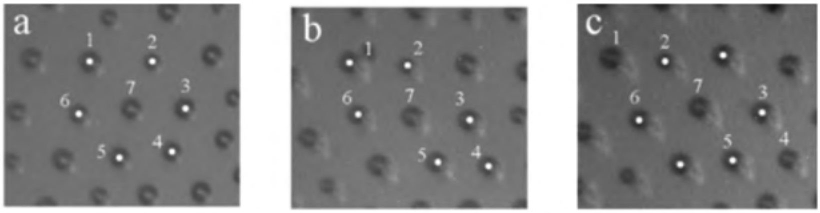


Figure 8: Hexagonal ordering is formed by droplets in the smectic film at certain moments of time. The droplets denoted 1, 2 and 4, 5 move in opposite directions with respect to the row of droplets 3, 6, and 7. Hexagonal ordering (a) is destroyed (b) and then reconstructed after some time (c). Numbers indicate droplets forming the hexagonal structure in frame (a). White dots in frames (a, c) show the droplets with hexagonal ordering. Dots in (b) denote the droplets that formed the hexagonal structure in frame (a). Frame (b) is taken 55 s after frame (a), frame (c) 95 s after frame (a). The horizontal size of the images is 191 µm.

In Figure 8a, the droplets move nearly along the bigger diagonal of the hexagon (the horizontal direction in Figure 4a with velocity gradient in the perpendicular direction). To facilitate tracking, droplet centers that formed a hexagon in Figure 8a were marked by white dots and numbered. The velocity of droplets in the upper and lower sides of the hexagon with respect to its center differed in terms of magnitude and direction, leading to the destruction of the hexagonal structure (Figure 8b) and its reappearance later. Then the hexagonal ordering was again destroyed. The structure formed by droplets in which the hexagonal order periodically disappears and reappears can be considered to be an analogue of the classical "time crystal." In our observation, a nearly constant gradient of mean velocity was created only in the nearest three rows of droplets.

It is worth noting that if the constant gradient of velocity were created in a larger number of rows, one would expect a much richer behavior; e.g., appearance of a line of hexagons perpendicular to the motion of droplets in discrete moments of time. These outcomes are determined by the velocity of the row of hexagons with the smallest velocity.

Discrete time crystals were realized in several quantum systems, but this result may be the first observation of time crystalline behavior in classical systems.

Multiphase Flow and Heat Transfer

This research area, which has applications in the fluid flow and engineering of thermal management and purification systems, focuses on complex problems of two-phase fluid flow (Chiaramonte and Joshi, 2004). Scientists are seeking to understand how gravity-dependent processes such as boiling and steam condensation occur in microgravity. Boiling is known to be an efficient way to transfer heat, and it is often used for cooling and energy conversion systems. In space applications, boiling is preferable to other types of energy conversion systems because it is efficient and the apparatus needed to generate power is smaller. Diffusive transport is another mechanism by which energy and matter (atoms, molecules, particles, etc.) move through liquids and gases.

The way atoms and molecules diffuse through a liquid or gas is due primarily to differences in concentration or temperature. Researchers use microgravity to study diffusion in complex systems, a process that would normally be eclipsed by the force of gravity. Understanding the physics of multiphase flow and heat transfer in space will enhance the ability of engineers to solve problems on Earth as well. Potential applications of this research include more effective air conditioning and refrigeration systems and more efficient power-generating plants.

Figure 9: Zero Boil-Off Tank (ZBOT) hardware in the Microgravity Science Glovebox (MSG) aboard ISS with Astronaut Joe Acaba.

As precursor to ISS investigations, three multiphase flow experiments were conducted aboard the space shuttle.

The Vented Tank Resupply Experiment (VTRE) was conducted to test improved methods for in-space refueling (Chato and Martin, 1997). VTRE used vane Propellant Management Devices (PMDs) to separate the liquid and gas phases of Refrigerant 113 in low gravity.

Experiment objectives included testing the capability of the vane PMDs to retain liquid during transfer between the two tanks, liquid-free venting of pressure, and recovery of liquid into the PMDs after a thruster firing.

The Tank Passive Control Experiment also used Refrigerant 113 to demonstrate the effectiveness of a low-velocity axial jet to mix the fluid and thereby control its pressure (Bentz, et al., 1997). Pressure increases of the volatile fluid were induced with heaters, simulating the in-space storage of a cryogenic fluid. Pressure control was found to be effective and repeatable at both high- and low-fluid fill levels over a wide range of jet velocities with varying amounts of non-condensable gases in the ullage for a variety of liquid/vapor orientations and heat inputs. Pressure spikes caused by explosive boiling were sometimes observed during heating at low-heat fluxes but were controllable with gentle mixing.

The Pool Boiling Experiments (PBE) conditioned liquid (R-113) to an initial, precisely defined pressure and temperature and subjected the liquid to a step-imposed heat flux from a semi-transparent, thin-film heater to initiate and maintain boiling for a defined period of time at a constant pressure level (Merte, et al., 1998). Transient measurements of the heater surface and fluid temperatures near the surface were made, and two simultaneous views from beneath the heating surface and from the side were recorded.

Several modes for propagation of boiling across the heater surface and subsequent vapor bubble growth were observed. Of particular interest were the extremely dynamic or "explosive" growths resulting from the large increase in the liquid-vapor interface area associated with the appearance of a wavy interface, which itself is due to the presence of an instability. Small vapor bubbles migrated toward and coalesced with a larger bubble at the combination of the lower heat flux levels and highest subcooling levels. This phenomenon enhanced the heat transfer by approximately 30 percent.

More recently aboard the ISS, several multiphase flow experiments have been conducted and are described below.

Boiling eXperiment Facility

The Boiling eXperiment Facility used normal perfluorohexane to conduct two experiments on the ISS: The Microheater Array Boiling Experiment (MABE) and the Nucleate Pool Boiling eXperiment (NPBX).

MABE used an array of 96 transparent individually-controlled microheaters to perform experiments over a wide range of heater and liquid temperatures, pressures and heater sizes (Raj, et al. 2012). Experiments have revealed two regimes for predicting pool-boiling behavior: Buoyancy Dominated Boiling (BDB) and Surface

Tension Dominated Boiling. Within the BDB regime, as the vapor bubble grows larger the density difference between the vapor bubble and surrounding liquid causes gravity to push the bubble off the heater surface and rise through the liquid. Liquid rushes in behind the bubble, and the process of heating and boiling repeats. This behavior has been observed for a wide range of acceleration (gravity) levels, ranging from high gravity (>1 g) to less than lunar gravity (1/6 g). At lower gravity levels, the boiling behavior is controlled by surface tension whereby a bubble covers a large portion of the total heater surface. Its growth is fed both by vaporization of liquid and by merging with smaller vapor bubbles that surround the large bubble. Its size is limited by condensation along the bubble surface that is in cooler liquid away from the heater.

Based on high-quality microgravity data (a/g<0.000001), a gravity scaling parameter for heat flux was modified to account for these ISS results, primarily based on parabolic aircraft flight experiments (a/g~0.01). While the aircraft flights were instrumental in developing the model, residual fluctuations on the aircraft significantly affected the boiling behavior, which is why the ISS environment was critical.

The robustness of this framework in predicting low-gravity heat transfer is further demonstrated by predicting many of the trends in the pool-boiling literature for several different fluids over a range of heater sizes, gravity levels, and those that previously could not be explained by any single model.

NPBX used a polished aluminum disc heated by strain gage heaters. Four cylindrical cavities were located at the corners of a square with a fifth cavity in the middle. The results of the experiments showed that a single bubble continues to grow to the size of the chamber without departing from the heater surface (Dhir, et al., 2012). During lateral merger of bubbles at high superheats (the difference between the heater and liquid temperature), a large bubble may depart from the surface but continue to hover near it. Neighboring bubbles are continuously pulled into the large bubble. At smaller temperature differences, bubbles at neighboring sites simply merge to yield a larger bubble. The larger bubble mostly positioned itself in the middle of the heated surface and served as a vapor sink. The latter mode persisted when boiling was occurring all over the heater surface. Heat fluxes for steady-state nucleate boiling and critical heat fluxes were found to be much lower than those obtained under 1 g.

Zero Boil-off Tank Experiment

The Zero Boil-Off Tank (ZBOT) experiment is a series of small tank pressurization and pressure control experiments using perfluoro-n-pentane (PnP; C5F12), a transparent volatile simulant fluid. The ultimate goal is to enable long duration storage of cryogenic propellant and life support liquids and the associated pressure control of the storage tanks. This pressure control is governed by interdependent mechanisms of forced mixing of the liquid, gravity-dependent transport processes in the liquid and vapor, and evaporation and condensation at the liquid/vapor interface. A comprehensive two-phase Computational Fluid Dynamics model also has been developed to predict tank pressure behavior for validation with microgravity experiment data (Kassemi, et al., 2018 (A-C)).

The test cell, made of polished optical quality cast acrylic, consists of a cylindrical midsection capped at each end by hemispherical domes. The device is equipped with a temperature-controlled vacuum jacket and a surface-mounted strip heater to heat the tank fluids, a temperature-controlled liquid jet flow to cool and mix the fluids, and a screen-type liquid acquisition device (LAD) to ensure that only liquid is withdrawn from the tank. The test-cell diagnostics include Resistance Temperature Detectors (RTDs) for temperature measurement, a pressure sensor, image capture of the ullage with white light illumination, and particle image velocimetry and flow visualization with a laser light sheet.

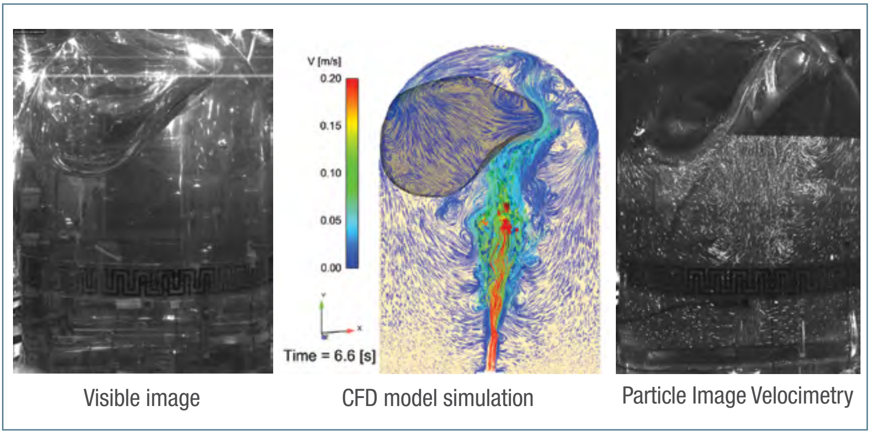


Figure 10: Zero Boil Off Tank (ZBOT) Experiment: Depiction of fluid flow and vapor bubble deformation by a liquid jet in microgravity.

For vacuum jacket and strip heating, the microgravity results for tank pressure rise are similar to that in normal gravity, although the rate and magnitude of the pressurization are lower than in normal gravity (Kassemi, et al., 2018 (C)). Jet mixing yielded a surprising and non-intuitive result wherein the ullage moved towards the jet nozzle at low jet speeds, while at higher speeds, the ullage remained in the upper portion of the tank but moved laterally to accommodate the passage of the jet. Ullage penetration and puncture by jet impingement was never observed. Pressure control by an uncooled jet was minimal and ineffective; a subcooled jet, however, produced a rapid initial pressure drop followed by further depressurization at a continuously decreasing rate. Flow visualization from the particle images showed several vortices produced in the tank during jet mixing. Surprising and non-intuitive immense phase change, suspected to originate at the screen LAD, was observed during subcooled jet mixing where the tank was filled initially with small bubbles that subsequently grew and coalesced. It is postulated that massive nucleate boiling might have occurred at nucleation sites on the screen LAD when the saturation temperature due to depressurization fell below the LAD temperature.

Packed Bed Reactor Experiment

The Packed Bed Reactor Experiment (PBRE) was developed and flown on the ISS by NASA to conduct a series of fundamental studies of gas-liquid flows through porous media. Flow through porous materials for space applications is encountered in life support systems, fuel cells, chemical/materials processing and when transporting nutrients to plants. These systems operate differently in the microgravity environment because the density differences no longer cause the phases to separate or "drain" under the force of gravity. In the absence of gravity, the interfacial or capillary forces play a more significant role in determining operational parameters such as phase distribution, liquid holdup, and pressure drop. This difference is most apparent when the liquid inertia and viscous forces are minimal, which is common for the space processes mentioned above; i.e., lower liquid flow rates within air/water systems.

The objective of this experiment was to better understand and improve upon the design and operation of space-based porous media flows where both a gas and liquid phase are present. During the early days of the ISS assembly, NASA flew a series of parabolic aircraft flights to develop a semi-empirical prediction for pressure drop and flow pattern transition for two-phase flows through porous media (Motil, et al., 2003). These studies included a range of packing sizes, column diameters, and liquid viscosities. However, important limitations to the aircraft flights included only

Figure 11: Packed Bed Reactor Experiment (PBRE) Test Section and Diagnostics.

a short time interval of low gravity (~20 sec) followed by a high gravity "pull-up" of the aircraft, which quickly drained the vertically positioned test sections. The range of flow rates typical in water reclamation processes take several minutes or longer to develop steady flow conditions, requiring extrapolation of the semi-empirical models developed under these earlier tests. These models were validated at the lower flow rates during the ISS testing (Sagli and Balakotaiah, 2016).

Constrained Vapor Bubble Experiment

The Constrained Vapor Bubble Experiments (CVB-1 and CVB-2) were based on a transparent, wickless, heat pipe and studied the influence of interfacial and intermolecular forces on the flow dynamics and heat transfer mechanisms that arise using a perfectly wetting working fluid, pentane, and a perfectly wetting working fluid mixture, pentane/isohexane (Plawsky and Nguyen, 2017). Three different lengths of heat pipe were run, including a reference heat pipe that contained no working fluid. Temperature profiles and internal pressures were measured as functions of input power to the heater and temperature set point of the cooler. Optical interferometry was employed to measure the liquid film thickness on the walls of the device from which the shape of the vapor-liquid interface and flows of liquids were determined.

The experiment revealed some surprising features of microgravity wickless heat pipe operation that had never been observed before. Instead of drying out at high heater temperatures, the hot end of the device flooded with liquid. The performance degradation under those conditions was indistinguishable from classical dry-out. Intermolecular forces were strong enough to induce condensation at the heater end even though the wall temperatures in that region were over 100ºC above the boiling point of the liquid inside the heat pipe. The length of the heat pipe had a great effect on the performance, and when the liquid flow design capacity of the device was exceeded, nature took over and interfacial-force-driven (Marangoni) rip currents were established that increased the extent of the vapor-liquid interface and enhanced the evaporative capacity of the device.

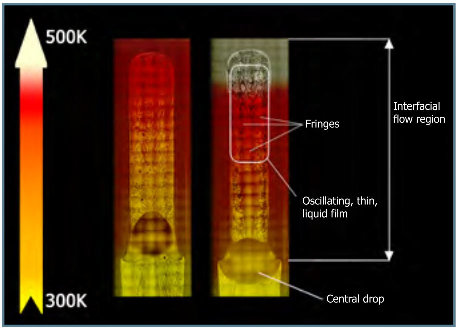


Figure 12: Surface condensation on the walls of a heat pipe is revealed by interference fringes (light and dark lines). Within the heat pipe is an "interfacial flow region" that extends from the hot evaporator at the top of the figure to the central drop. The condenser heat pipe is not shown and is below the central drop. The amount of surface condensation, as indicated by the density of fringes, is greater near the evaporator for the hotter heat pipe on the right than it is for the relatively cool heat pipe on the left (Kundan, et al., 2017). The background grid structure appears in the background because these figures are actually composites of several images.

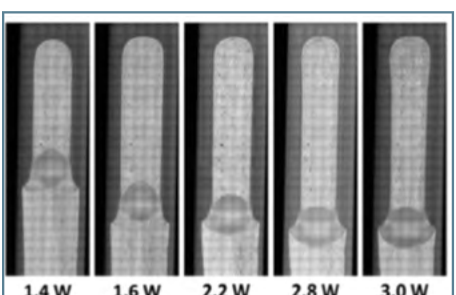


Figure 13: Composite images showing the development of the interfacial flow region, the central drop morphology and the origin and dissipation of the rip current as a function of heat input. The same Marangoni Forces responsible for the development of the interfacial region also serve to dissipate the rip current as it approaches the heater wall of the device (Kundan, et al., 2015; Nguyen, et al., 2018).

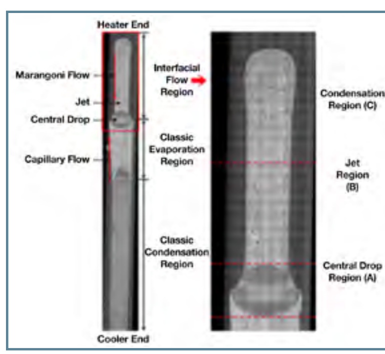


Figure 14: Left: 10X composite interferometry image of the CVB heat pipe taken at 3W heat input when the spontaneous rip current is the strongest. The rip current serves to increase the interfacial area and enhance evaporative heat transfer. Right: A magnified image of the heat pipe highlights just the rip current and the three main sub-regions of interest within the overall interfacial flow region. (Kundan, et al., 2017; Nguyen, et al., 2018).

Interfacial Phenomena/Capillary Flow

Fluid dynamics, instabilities and interfacial or capillary flows constitute another important subset of fluid physics. Capillary flows and phenomena are applicable to a myriad of fluids management systems in low-g, including fuel and cryogen storage systems, thermal control systems (e.g., vapor/liquid separation), life support systems (e.g., water recycling), and materials processing. In fact, NASA's near-term exploration missions plan larger liquid propellant tanks than have ever flown for interplanetary missions. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that large mission-critical systems perform predictably.

Interfacial phenomena are driven by surface tension and the contact angle or degree of wetting, which depend on both the fluid and the adjoining surface. Capillary forces are masked by the gravitational force exerted on fluids, hence the need to study these phenomena under low-gravity conditions. Because hydrostatic pressure is absent in microgravity, technologies for liquid management in space use capillary forces to position and transport liquids. On Earth, the effect of capillary forces is limited to a few millimeters. In space, these forces still affect free surfaces that extend over meters. For the application of open channels in propellant tanks of spacecraft, design knowledge of the limitations of open capillary channel flow is a requirement. These limitations are based on the restriction that the liquid fuel must be free of bubbles prior to entering the thrusters.

Early drop tower experiments established the need to understand the effects of interfacial phenomena in a microgravity environment (Siegel, 1961). The first spaceflight microgravity experiment was an interfacial phenomena investigation performed by astronaut Scott Carpenter on Mercury flight MA-07 in 1962. In particular, it tested fluid equilibrium configurations in a cylindrical-baffle-in-a-sphere geometry (Petrash, et al, 1962; Petrash, et al, 1963).

Recent experiments flown on the ISS include the Capillary Flow Experiments (CFE- 1, CFE-2) and the Capillary Channel Flow (CCF) experiment. CFE-1 and CFE-2 were a suite of experiments that investigated capillary flows and flows of fluids in containers with complex geometries. CCF investigated capillary and interfacial phenomena in inertial-dominated flows. Results from these experiments are expected to improve current computer models that are used by designers of low-gravity flow systems and lead to improved fluid transfer systems on future spacecraft.

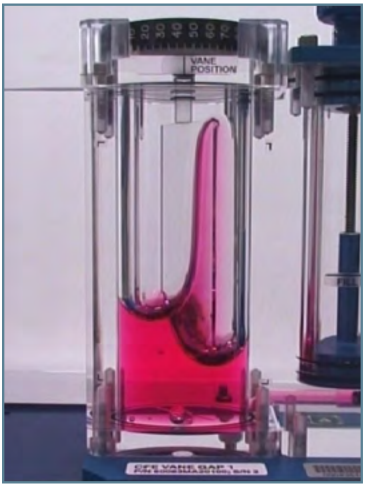
CFE-1 was a simple fundamental scientific study and consisted of a set of six separate fluid physics flight vessels that investigated capillary flows in low gravity. The CFE data are crucial to aid in design of fluid management systems, including fuels/cryogen storage, thermal control, water recycling and materials processing. Under low-gravity conditions, capillary forces can be exploited to control fluid orientation so that these mission-critical systems perform predictably.

The experiments provided critical results to the capillary flow community:

- Dynamic effects associated with a moving contact boundary condition.
- Capillary-driven flow in interior corner networks (Weislogel, 2012).
- Critical wetting phenomena in complex geometries.

Figure 15. Image sequence of Interior Corner Flow2 bubble migration where each image is approximately 60 seconds apart. The bubble location measurements, z1 and z2, are tracked and compared with analytic and numeric predictions.

CFE included the Interior Corner Flow (ICF1, ICF2), the Vane Gap (VG1, VG2), and the Contact Line (CL1, CL2) experimental units. All units used similar fluid injection hardware, had simple and similarly sized test chambers, and relied solely on video for highly quantitative data. The test fluid was a silicone oil with viscosities selected for each unit. Other differences between units were wetting conditions and test cell cross-section. The ICF experiment investigated propellant management and passive capillary flow in tapered geometries for which boundary conditions are not well understood or modeled. The initial and secondary imbibition was investigated in two different tapering interior corner geometries. This set of experiments also tested the ability of these type of geometries to passively separate gas/liquid mixtures under low-gravity conditions. Figure 15 contains several time-sequenced images of the slow secondary imbibition in the ICF2 geometry.



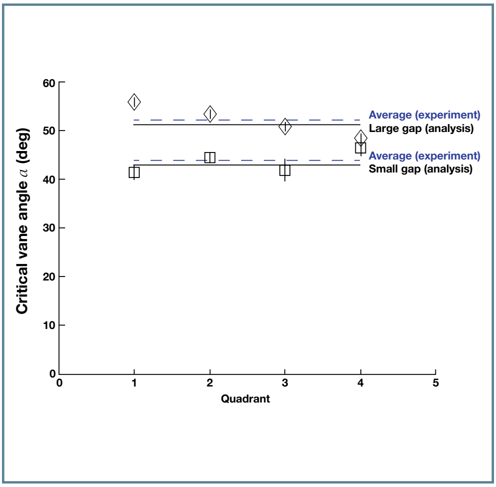


Figure 16. (a) Science image of the Capillary Flow Experiments Vane Gap-1 vessel at a 45° vane angle. A large "finger" of fluid has filled the gap between the vane and chamber inside the surface closest to the camera view at the critical angle of 45 degrees (within ±1.5 degrees of predicted value); (b) Test points like this one provide experimental verification of present analytic and numerical methods to predict such nearly discontinuous static and dynamic phenomena.

The VG experiment investigated the critical wetting condition when interior corners do not actually make contact, specifically the corner and gap formed by an interior vane and the interior wall of a propellant tank. The critical wetting angles have been measured to within ±0.5 degrees, nearly four times more accurate than planned (Chen, et al., 2012). In addition, a bulk shift phenomena has been discovered that has implications for spacecraft tank design asymmetries. Figure 16 contains an image of a critical wetting angle along with a plot of experimental wetting angle results versus theory predictions. Figure 17 contains a sequence of images of various angle positions during a complete 360-degree sweep of the vane in the test chamber.

The CL experiment studied the impact of the dynamic contact line. The contact line controls the interface shape, stability and dynamics of capillary systems in low-g. The two CL units are identical except for their respective wetting characteristics. For the CL experiments, data from over 350 primary and ancillary science events have been reduced, and significant contributions were found for both experimental results and numerical comparisons. The complete database can be found at http://cfe.pdx.edu. To date, the damped interface oscillations (frequency and decay) as functions of fluid properties, wetting, contact line condition, disturbance type and amplitude

Figure 17. Equilibrium interfaces for Vane Gap-1 for several vane dial angles: 0, 36, 43, 53, 59.5, 90, 127.5, 134.5, 150.5, 180 degrees (from top left to bottom right).

have been pursued. Figure 18 provides example images of the static and dynamic states for an experimental run.

The CFE-2 is a continuation of CFE-1 and investigates increasing complex capillary flow geometries. Four re-flight units and seven new units have been operated on ISS.

The CCF experiment is a versatile flight experiment for studying a critical variety of inertial-capillary dominated flows and is critical to spacecraft systems that cannot be studied on the ground.

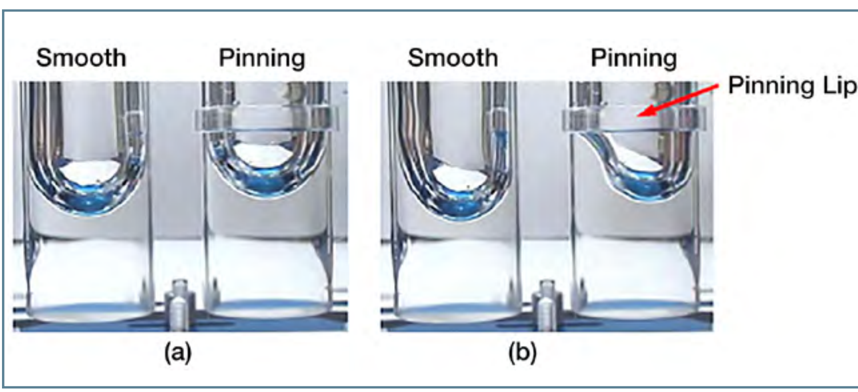


Figure 18. Image of Contact Line 2 showing smooth and pinning edge boundary conditions under (a) equilibrium, and (b) dynamic states.

The results of CCF will help innovate existing applications and inspire new ones in the portion of the aerospace community challenged by the containment, storage and handling of large liquid inventories (fuels, cryogens, and water) aboard spacecraft. The results will be immediately useful for the design, testing and instrumentation for verification and validation of liquid management systems of current orbiting, and future spacecraft envisioned for lunar and Mars missions. Results will also be

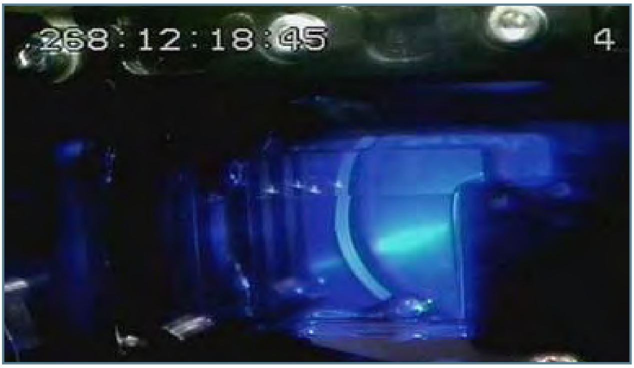


Figure 19. Capillary Channel Flow image of Experimental Unit #2 using second Microgravity Science Glovebox camera. The bubble in lower portion of image indicates the critical flow rate has been reached for this test point.

used to improve life support system design, separate the gas and liquid phases and enhance current system reliability.

CCF examines flows in parallel plate channels, grooves and interior corner capillary conduits. These conduits represent a class of practical capillary geometries that are implemented in designs of spacecraft fluid processing equipment. Validation of theoretical models developed for these geometries will increase confidence in the theory so that it may be applied to other geometries pertinent to advanced microgravity fluid systems development.

The test matrix for Experimental Unit #1, which included the parallel plate and groove channel geometries, collected over 1,300 data points with 900 consisting of high-speed, high-resolution video image (100+ GB of video data). Data analysis has verified model predictions for a number of critical conditions where the maximum flow rate occurs (Haake, et al., 2010). In general, the measured critical flow rates for the parallel plate and groove channel were within 3 percent of each other. Results also discovered several "new" unstable conditions, which do not appear to match existing theoretical models.

Over 3,000 test points were collected for the Experimental Unit #2. Figure 19 is from a video image of the critical velocity being reached during an experimental run. A series of regime maps have been generated that identify the passive gas/liquid separation regimes for the wedge-shaped geometry (Jenson, et al., 2014).

Further work is needed that emphasizes fluids challenges related to propellant tanks and water processing for life support. In particular, capillary-flow geometries that are tolerant to fickle wetting conditions, such as those that occur in spacecraft urine collection and water recycling systems, need to be further investigated.

Although ground-based work is already being pursued in these newer areas, the long-duration microgravity environment provided by ISS is needed for further experimental investigations such as:

- Experiments using capillary flow geometries that can purposely perform passive gas/liquid phase separation.
- Capillary flow investigations that include non-isothermal effects (evaporation/condensation), normally encountered in cryogenic systems, but also are encountered in proposed Environmental Control and Life Support Systems (ECLSS) that influence wetting conditions/contact angle.
- Fundamental areas of capillary flow, investigations that use idealized pore geometries to gain insight into capillary wicks, water uptake in soils, etc.
- Testing capillary geometries of interest in micro-fluidic applications such as for micro-scale diagnostic devices (also referred to as Lab-on-a-Chip), along with pumping and valving techniques, could be investigated before the manufacturing methods for fabricating these micro-scale features are available.

Opportunities for Research in Fluid Physics on ISS

Complex Fluids

The study of complex fluids encompasses diverse fields such as phase transitions, nucleation and crystal growth, glass formation, chaos, field theory, and much more. Furthermore, research in complex fluids provides the underpinnings of applications related to NASA exploration of planetary surfaces as well as terrestrial applications in industries such as pharmaceutical, chemical, plastics, petroleum, electronics, liquid crystals, and the next generation of high-resolution inks for additive manufacturing. According to the National Research Council Decadal Survey (Space Studies Board, 2011), these industries contribute over $1 trillion annually to U.S. manufacturing output.

The need to conduct research in a microgravity environment is clear. Because of the relatively large size of the basic structures, gravitational forces dominate, causing sedimentation, particle jamming, convective flows and other induced gradients, and obscuring weaker forces such as surface tension and entropic forces. In granular materials, stresses and yield properties are also sensitive to gravity.

Colloids and Suspensions

Future fundamental studies of order, including the role of colloidal particle shape on structure and complex processes such as self-assembly, motility and non-biological self-replication, are key research areas to address and will require a microscope with the following desired capabilities:

- Faster imaging rate for quickly constructing 3D confocal images with a higher-resolution. Scientists are beginning to observe new and interesting behaviors when the frame rate is increased above 100 frames-per-second.
- Particle and cluster manipulation capabilities using dynamic laser tweezers that allow scientists to manipulate samples and to introduce defects to see and understand how nature heals. Dynamic laser tweezers will also enable scientists to grow ordered structures from patterned layers that can be laid down by the laser tweezers, patterns whose spacing can also be manipulated in this way. This technology will enable scientists to see what nature prefers and how to best coax her when another structure or pattern is needed to realize a needed technology.
- Homodyne dynamic light scattering to measure particle diffusion coefficients in regular sample cells and in temperature gradient cells (to provide phase diagram location and translational and rotational diffusion coefficients).
- Spectrometry capabilities for quantifying new colloidal crystals and their growth rates. This option will be useful for investigations such as seeded growth

studies where growth rates and other properties of homogeneous and controlled heterogeneous crystals can be compared.
- Variable crossed-polarizers for quantifying the polarization rotation predicted for liquid crystals and new types of materials.
- Vibration cancelling three axes Piezo-platform for holding samples that will significantly improve submicron imaging and 3D confocal image sectioning and image reconstruction.

In addition, the Physics of Colloids in Space (PCS) experiment studied the phase behavior, growth dynamics, morphology and mechanical properties of different types of colloidal suspensions, including binary colloidal alloys, colloidal polymer mixtures, fractal colloidal aggregates, and the natural entropy-driven transition from a disordered glassy state to an ordered crystalline one. This EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Rack hardware, with its dynamic light scattering, Bragg scattering, and low-angle scattering measurement capabilities, was put into bonded-storage for possible future use on ISS.

Liquid Crystals

An important area of soft condensed matter physics and chemistry that has seen major discoveries and rapid advancement with immediate application for consumer electronics is the study of liquid crystals. Increased understanding of the dynamics, morphology and structures of liquid crystals significantly enhances the ability to control the properties of this type of complex fluid. Liquid crystals are incredibly important as a fundamental material for modern display and information storage and processing technologies as well as possible high-efficiency energy conversion devices.

The study examines the two-dimensional fluid physics of freely suspended liquid crystalline (FSLC) films, including overall fluid motion, diffusion and merging of extra film layers called islands. In the microgravity environment, recent experiments tested theories of 2D hydrodynamic flow, of relaxation of hydrodynamic perturbations, and 2D hydrodynamic interactions. Since there is no natural convection in microgravity, freely suspended bubbles present an ideal fluid system for the study of 2D hydrodynamics.

While much work has been done in understanding the growth kinetics process in other systems such as crystallization and the phase separation of binary alloys, only recently has the phase ordering process been studied in systems that form liquid crystals. Systems that form liquid crystal are good candidates for studying phase ordering kinetics since they can be observed directly using Depolarized Reflective Light Microscopy, which will be available in the near future aboard station fluid facilities.

Foams

Foams are dispersions of gas into liquid or solid matrices. Typically, they are made in conditions where the matrix is liquid. The behavior of foams in microgravity is different from on Earth because the process of drainage is absent in microgravity conditions. Drainage is the irreversible flow of liquid through the foam leading to the accumulation of liquid at the foam bottom and to a decrease of global liquid content within the foam; in this case, the gas bubbles conform to the polyhedra in the upper portion of the foam, creating a so-called "dry foam." When the liquid films between the bubbles become very thin, they break, collapsing the foam. This happens in the absence of suitable stabilizing agents (well-chosen surfactants or solid particles for aqueous foams).

Microgravity offers the opportunity to investigate the so-called "wet" foams, which cannot be stabilized on Earth because of the drainage problem. New behaviors or regimes are expected to appear for wet foams, masked by convective instabilities on Earth. In addition, elastic and viscous properties of wet foams are expected to be strongly modified by the presence of solid particles. The physics of wet foams is, therefore, poorly understood.

Granular Materials

Granular matter is the most common and pervasive medium after air and water, yet the understanding of its statics and dynamics lags significantly behind that of conventional solids and fluids. Specifically, the rationally derived constitutive relationships between strain, or strain rates, and the stresses in granular media are not understood. Without this understanding, the ability to predict the dynamics of granular materials and to design the associated equipment is severely limited.

ISS flight experiments could develop and test models for both static (jammed) and dynamic (flowing) states. In parallel, an experiment could be developed to conduct simulated technology applications for this research area to include studying "icy regolith" flows where the effects of ice and water on material handling are investigated.

Particulate Management

Particulate management is similar to the behavior of granular materials; however, the concentration of the solid particles is extremely low in the bulk fluid but can accumulate in localized volumes to have detrimental effects. "Dust" can have varying effects on system components. It can degrade the movement of mechanical parts, penetrate seals, obscure optical surfaces (e.g., windows) and sensors, and short out electronic components. Airborne or suspended micron- and sub-micron-size particles are particularly problematic since their persistence in large concentrations can pose acute health problems.

The fundamentals of aerosol transport are well known for terrestrial applications. However, given the indefinite residence times in transit and orbiting vehicles, the dust capturing that takes place in the ventilation and filtration systems leads to extended particle-to-particle interactions. Areas of poor ventilation or flow stagnation regions are more susceptible to dust buildup. A detailed look at these mechanisms under the microgravity environment and large aggregate loading conditions provides valuable engineering information on the best approaches for dust capturing controls. These approaches can include investigations on fibrous capturing mechanisms, impaction, interception and diffusion, and alternate approaches such as inertial, electrostatics and surface/fiber coatings. The added effects of reduced-pressure environments are also factors.

Magnetorheological Fluids

Magnetorheological fluid suspensions are normally stable fluid suspensions that undergo a dynamic mechanical transition to a solid within milliseconds after the application of an external magnetic field. This rapid and reversible transition in the material's mechanical behavior is due to the distinct microstructural transition in the fluid driven by the polarization of particles. The mechanical energy required to strain and disrupt such networks leads to elasticity and yielding, but the suspension reverts to liquid-like behavior almost immediately after removing the field.

Magnetorheological fluid provides the basis for technologies ranging from actively controlled dampers and actuators to magnetically sealed bearings and sensitive stress transducers.

Applications in space exploration include potential use in robots, rovers and crew suits (mobility augmentation), especially for endurance and fatigue countermeasure designs that aid in lifting, moving and supporting loads during extra-vehicular activities (i.e., spacewalks). In addition to their immediate applications in mechanical systems, Magnetorheological fluid suspensions have become important components in microfluidic devices that could lead to compact medical instrumentation and diagnostics for Earth-based and long-duration spaceflight applications.

Polymer Fluids

The combination of both shearing and extensional flows is common in many polymer processing operations such as extrusion, blow molding and fiber spinning. Therefore, knowledge of the complete rheological properties of the polymeric fluid being processed is required in order to accurately predict and account for its flow behavior. In addition, if numerical simulations are to serve as a priori design tools for optimizing polymer processing operations, then it is critical to have an accurate knowledge of the extensional viscosity and its variation with temperature, concentration, molecular weight and strain rate.

Multiphase Flow

The gas-liquid interface is the focus of multiple phenomena involving interactions among bubbles, drops and solid objects. It is also the boundary across which momentum, mass and heat transfer occur. Although studies have been conducted on the interactions of the interface in reduced gravity, most careful measurements have been made with limited systems consisting of only a handful of bubbles and drops and have not been complicated by bulk fluid motion and phase change. The results of these studies are not sufficient to develop predictive models to describe multiphase flow behavior in microgravity.

Phase density and interfacial tension dominate the behavior of multiphase systems in reduced gravity unlike that in normal gravity. While phase density in normal gravity results in a buoyancy-driven segregation of the phases and distortion of the shape of the interface, the impact of the phase-density difference is primarily evident in the flow momentum, which is demonstrated by the flow distribution in splitting tees and cyclonic separators. Interfacial tension in reduced gravity causes the gas-liquid interface to become more spherical at larger length scales. It is necessary to develop a fundamental understanding of multiphase flow behavior and of the momentum, heat and mass transfer processes in microgravity. Discrete critical parameters should be measured experimentally to develop and validate predictive models (Lahey, et al., 2004). These models are essential tools needed by designers of life support, propulsion, power and other systems for use in space and on the moon and Mars.

It is necessary to examine Two Phase Flow Instability Mechanisms. These mechanisms are heavily influenced by the gas/vapor phase density and its compliance

(Ledinegg Instability) with system controls such as pressure control systems or pump characteristics. Phase distribution in manifolds for parallel channel evaporators and condensers is governed by both phase momentum and interfacial phenomena.

Zero Boil-off Tank Experiment Series

The storage, conditioning and transfer of volatile fluids is the focus of the series of experiments planning to use the Zero Boil-Off Tank experiment hardware. The ZBOT hardware is a highly instrumented tank and flow loop and includes visualization and other diagnostics to capture the simulant fluid behavior within a transparent tank in an effort to understand the governing parameters required for cryogenic fluid and thermal management. Planned uses include examining the effect of non-condensable gases on the thermal conditioning and pressurization of volatile fluid, active cooling through use of spray bars and/or cold fingers, and transfer line and receiving tank chill down.

ElectroHydroDynamics

Application of an electric field on the order of 1 kV/cm (or higher) to a dielectric fluid (semi-insulating fluid) results in electrohydrodynamic (EHD) pumping of the dielectric fluid. The EHD conduction pumping is based on the interaction of fluid flow field and external electric field via the Coulomb force, which involves the dissociation and recombination of neutral species where the rate of dissociation exceeds that of recombination.

In addition to EHD conduction pumping, a second EHD mechanism is based on the dielectrophoretic (DEP) force. Unlike the Coulomb force, the DEP force acts on polarized charges and can be used to significantly influence vapor bubble motion (e.g., effectively extracting the vapor bubbles away from the heated surface) during nucleate boiling.

The EHD experiment seeks to develop fundamental understanding on the interaction of electric and flow fields in the presence of phase change (liquid/vapor). The EHD experiment is a parametric investigation of thin film liquid boiling phenomenon employing a dielectric fluid as the liquid. The schematic of the experiment and a photo of the test cell showing the EHD disc and the DEP electrodes in Figure 20.

Adiabatic Gas-Liquid Flow Experiments

The Packed Bed Reactor Experiment (PBRE) provides a nitrogen gas and water

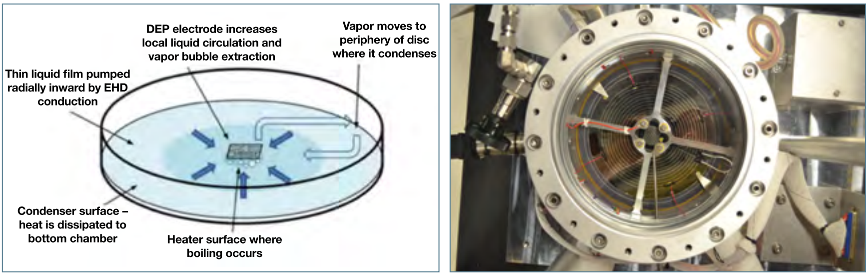


Figure 20: Left: This experiment concept for the test chamber: a dielectrophoretic (DEP) electrode removes vapor bubbles from the heater. The surrounding circular electrode strips centered on the heater pump cool the single-phase liquid back toward the heater. Right: Image of prototype test chamber.

flow to a replaceable test section and diagnostics and can provide opportunities to conduct a number of different types of future experiments. A wide range of precisely controlled gas and liquid flows can be provided that envelop the flow ranges typically encountered in most adiabatic two-phase devices used for water processing or thermal control. Diagnostics including high speed video, pressure drop, and flow rates are available. Testing can include new reactor beds as well as fluid components and systems.

Flow Boiling and Condensation Experiment

The Flow Boiling and Condensation Experiment (FBCE) is a two-phase flow boiling/condensation facility aboard the ISS that serves as the primary platform for obtaining two-phase flow and heat transfer data in microgravity. The key objectives of the experiment are:

- Develop an experimentally validated mechanistic model for microgravity flow boiling Critical Heat Flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF.
- Develop experimentally validated mechanistic model for microgravity annular condensation and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent annular condensation. In addition, develop correlations for other condensation regimes in microgravity.
- Obtain flow boiling data (heat flux, the wall temperature difference) in long duration microgravity environments for a well characterized heating surface as functions of liquid inlet mass velocity and sub-cooling.
- Obtain flow condensation data (heat flux, the wall temperature difference) in long duration microgravity environments for a well-characterized condensing surface as functions of inlet quality and flow rate of condensing vapor.

The FBCE hardware conditions the test fluid (normal-perfluorohexane or nPFH-C6F14) to the proper thermodynamic state before entering the Flow Boiling or the Condensation test modules and reconditioning of the test fluid to enter the pump as a subcooled liquid.

Figure 21: Flow Boiling and Condensation Experiment (FBCE) Test Sections: Top: Condensation Module-Heat Transfer (CM-HT), Middle: Condensation Module-Flow Visualization (CM-FV) Bottom: Flow Boiling Module (FBM).

The FBCE will be conducted in the Fluids Integrated Rack (FIR) on board the station. Three different test modules are planned (Figure 21):

1) The Flow Boiling Module (FBM) includes a boiling section with a rectangular cross-section and individually powered wall heaters on the top and and bottom of the test section. This module is highly instrumented with therma couples and can be visualized with a high-speed imager along its length.

2) The condensation module-heat transfer (CM-HT) is configured with the test fluid flowing inside a cylindrical tube while water flowing outside the tube removes the heat released from condensation. The test section is highly instrumented with thermocouples.

3) The condensation module-flow visualization (CM-FV) is designed so that the cooling water flows inside a tube while the vapor condenses on the tube exterior. CM-FV also measures temperatures but not as comprehensively as CM-HT.

Capillary, Thermocapillary and Solutocapillary Flow Phenomena

Capillary flows and phenomena are applicable to a myriad of fluids management systems in low-g, including fuel and cryogen storage systems, thermal control systems (e.g., vapor/liquid separation), life support systems (e.g., water recycling), and materials processing in the liquid state. In fact, NASA's near-term exploration missions plan larger masses of liquid propellant than have ever flown on interplanetary missions. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that such large, mission-critical systems perform predictably.

Many multiphase flow phenomena in reduced gravity are driven by variations in surface tension caused intentionally or inadvertently because of gradients in temperature, concentration or wetting conditions. Such flows, also called thermocapillary/solutocapillary flows or Marangoni convection, find application in most fluid systems in space such as propellant management systems, thermal control systems, cryogenic fluid systems, life support systems, etc. Fluid systems in which bubbles, drops and nucleation phenomena occur are particularly susceptible to flows driven by surface tension gradients.

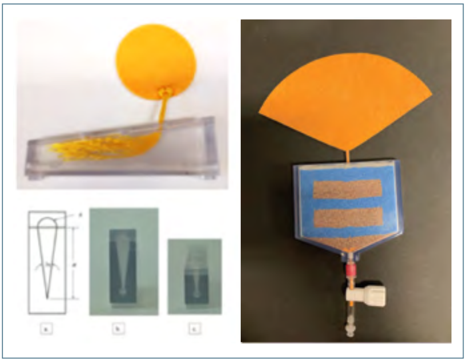


Figure 22: Simulated plants constructed of felt foliage and string roots mimic plant water uptake. Plant Water Management involves addressing challenges in both hydroponics channels (left) and soil-based media (right) using capillary fluidics.

For example, a capillary-based approach is needed to provide sufficient hydration and aeration to the root zone for growing plants. Plants require water for nutrient transport, biochemical processes, and thermal management. Aeration is required for the root zone to exhale carbon dioxide and inhale oxygen at a minimal but necessary level. The Plant Water Management experiment is a technical demonstration of new techniques in capillary flow phenomena. This experiment intends to demonstrate methods that exploit passive and semi-passive control of poorly wetting capillary liquids that mimic the role of gravity on earth. Specifically, we intend to demonstrate the extent to which capillary forces may be exploited to control numerous effects on low-g plant watering for both soil-based growth media and hydroponics channels while considering critical challenges of saturation, de-gassing, aeration, stability, and more.

Lessons Learned

The NASA Colloids Program has prompted several paradigm shifts in soft condensed matter physics. New areas of inquiry stem from the following recent findings:

- observations of the disorder-to-order transition (glasses on Earth crystallizing in microgravity),
- crystallization arresting phase separation,
- fluids with critical points far from where theory predicted them to be; e.g., bi-disperse systems showing unexpected behaviors, such as particle stabilizer particles that are 20 percent smaller do not form clusters in the presence of dilatant attractants in the same way as larger particles,
- seed particles affecting the type of nucleation being observed.

Analysis of experiment data revealed interesting elastic instabilities on the free surface of a fluid sample. The data showed the formation of beads-on-a-string structures in the absence of gravitational sagging. The development and evolution of such phenomena upon cessation of elongation have not yet been described.

The design of a heat transfer experiment should account for extreme heating that could cause thermal decomposition of the test fluid. Consequently, heater temperatures should be measured directly and incorporated into control/protection circuit, and these heaters and other convective heat devices should be derated from normal to microgravity operation. The electrical system of any experiment should be designed so failed components can be isolated in order to maintain maximum capabilities in the event of a failure by individually fusing heaters and using independent controls to activate/deactivate them.

Complexity of the experiment should be minimized if at all possible. Science requirements that add complexity not only add additional cost to the development, but often lengthen the development time, making turnover an issue for both the project team and, in particular, for the principal investigator and his/her science team when the experiment timeline extends beyond the typical tenure of a Ph.D. student. It is important to design the experiment to be both flexible and repairable. Unlike the space shuttle experiment days, the ISS operates more like a laboratory on Earth where crew members often gain rather good experimental skills while operating a particular experiment over months rather than a week or so. As a result, they can become quite adept at experiment repair if this capability is designed into the experiment and clear, straightforward procedures are provided.

ISS Facilities for Research of Fluid Physics

Acceleration Measurement and Environment Characterization

The Space Acceleration Measurement System (SAMS) and the Microgravity Acceleration Measurement System (MAMS) provide continuous measurement of the ISS vibratory and quasi-steady acceleration environment, respectively. SAMS measurement capability extends to all three laboratories, while MAMS data can be mathematically mapped to any arbitrary location using rigid-body assumptions.

SAMS and MAMS support NASA's Physical Sciences Research Program. Along with Principal Investigator Microgravity Services analyses, these systems serve a critical, ongoing role in support of vehicle/loads monitoring. SAMS and MAMS monitor vehicle dynamic loads and assist technology developers and principal investigators in various disciplines. The goal is to characterize and understand the acceleration environment as related to a wide array of disturbances and events that routinely or uniquely take place on the ISS.

Fluids Integrated Rack

The Fluids Integrated Rack (FIR) was designed to test and understand critical technologies needed for advanced life support and future spacecraft thermal control, research in complex fluids (colloids), and life science experiments. The hardware was delivered on STS-128 (August 2009) to the ISS and installed in the Fluids and Combustion Facility of the U.S. Lab. The FIR contains the hardware and software necessary for conducting fluid physics science experiments. It is designed to accommodate a range of fluids experiments while meeting ISS requirements and limitations such as safety, power and energy, cooling, mass, crew time, stowage, resupply flights, and data downlink.

The FIR uses six major subsystems to accommodate the broad scope of fluids physics experiments. The major FIR subsystems are structural, environmental, electrical, gaseous, command and data management, and diagnostics. These subsystems combined with payload- unique hardware allow the FIR to conduct world-class science. It also provides the largest contiguous volume for experimental hardware of any ISS facility, easily reconfigurable diagnostics, customizable software, active rack-level vibration isolation and other subsystems required to support a wide range of gravity-dependent fluid physics and life science investigations. The LMM, or microgravity microscope, is an integral part of this facility.

Light Microscopy Module

The Light Microscopy Module is a remotely controllable in-orbit microscope subrack facility, allowing flexible scheduling and control of physical science and biological science experiments within the FIR on the ISS. The LMM concept is a modified commercial research imaging light microscope with powerful laser-diagnostic hardware and interfaces, creating a one-of-a-kind, state-of-the- art microscopic research facility. The microscope will house several different objectives, corresponding to magnifications of 10x, 40x, 50x, 63x and 100x. Features of the LMM include high-resolution, color video microscopy, bright field, dark field, phase contrast, differential interface contrast, spectrophotometry, and confocal microscopy combined in a single configuration. The LMM provides an enclosed work area called the auxiliary fluids container with glove ports and an equipment transfer module for transporting experiment samples from stowage to the LMM.

Microgravity Science Glovebox

The Microgravity Science Glovebox (MSG) is a research facility installed on the ISS in which fundamental and applied scientific research is conducted in support of the NASA Headquarters' Vision for Space Exploration. This facility was designed to accommodate small science and technology experiments in a "workbench" type environment. Because the facility's working volume is enclosed and held at a negative pressure with respect to the crew living area, the requirements on the experiments for containment of small parts, particulates, fluids and gases in the low-gravity space station environment are substantially reduced. The concept allows scientific flight hardware to be constructed in close parallel with bench experiments developed in ground-based laboratories. The facility is ideally suited to provide quick accommodations for exploration investigations that are necessary to gain an initial understanding on the role of gravity in the physics associated with new research areas.

Research investigations operating inside the MSG are provided a large, 255-liter enclosed work space, 1,000 watts of dc power via a versatile supply interface (120, 28, +12, and 5 Vdc), 1,000 watts of cooling capability, video and data recording and real-time downlink, ground commanding capabilities, access to ISS Vacuum Exhaust and Vacuum Resource Systems, and gaseous nitrogen supply. These capabilities make the MSG one of the most utilized science facilities on the ISS. In fact, the MSG has been used for over 10,000 hours of scientific payload operations. MSG investigations involve research in cryogenic fluid management, fluid physics, spacecraft fire safety, materials science, combustion, plant growth, human health, and life support technologies. The MSG facility is ideal for advancing our understanding of the role of gravity upon science investigations and research, and to utilize the ISS as a technology platform for space exploration.

EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Racks

The eight EXPRESS racks are multi-use facilities, which provide standard interfaces and resources for Middeck Locker and International Subrack Interface Standard drawer payloads. Payloads using single-, double- or quad-locker and/or drawer configurations can be accommodated by these racks. The racks provide a number of services for payloads including Nitrogen, Vacuum, RS422, Ethernet, video, air, and water-cooling.

Developing and Flying Fluid Physics Research to ISS

The research community is provided specific research topics through NASA Research Announcements. In response, the research community generates ideas regarding the topics and submits them to NASA, which evaluates the responses and makes selections through a peer review process. Awards are granted for ground-based research at NASA and/or principal investigator institutions. Principal investigators are required to pass the Science Concept Review and Requirements Design Review. Flight research experiment concepts and designs undergo the Preliminary Design, Critical Design, and System Acceptance Review processes before fluids physics research is launched and conducted on the ISS.

PIs need to consider potential hazards (e.g., flammability, explosion, corrosion, toxicity) and their impact on both crew and spacecraft when selecting test fluids. Furthermore, additional hazards can result from the inadvertent release of the test fluid into ISS environment and potential reaction with ISS systems such as the catalytic converter in the Trace Contaminant Control Subassembly (TCCS). While additional levels of containment may mitigate hazards during the storage and operation of the experiment, other controls are needed to address the handling of fluids during filling and sampling procedures.

Additional Guides that may be of interest to fluid physics researchers include "A Researcher's Guide to the Acceleration Environment" and "A Researcher's Guide to Physical Sciences Informatics System." See https://www.nasa.gov/mission_pages/station/research/researcher_guide.

Funding, Developing and Launching Research to ISS

Supporting research in science and technology is an important part of NASA's overall mission. NASA solicits research through the release of NASA Research Announcements (NRAs), which cover a wide range of scientific disciplines. All NRA solicitations are facilitated through the web-based NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES) http://nspires.nasaprs.com/external/. Registering with NSPIRES allows investigators to stay informed of newly released NRAs and enables them to submit proposals. NSPIRES supports the entire lifecycle of NASA research solicitations and awards, from the release of new research calls through the peer review and selection process.

In planning the scope of the proposal, an investigator should be aware of available resources and the general direction guiding NASA research selection. NASA places high priority on recommendations from the 2011 National Research Council's Decadal Survey (Space Council Board, 2011) and subsequent reports, which placed emphasis on hypothesis-driven spaceflight research. In addition, principal investigators (PIs) should be aware that spaceflight experiments may be limited by a combination of constraints on power, crew time, or volume. Launch and/or landing scrubs are not uncommon, and alternative implementation scenarios should be considered in order to reduce the risk from these scrubs. Preliminary investigations using ground-based simulators may be necessary to optimize procedures before spaceflight. Also, many experiments require unique hardware to meet the needs of the spaceflight experiment.

To understand previous spaceflight studies, prospective PIs should familiarize themselves with the Physical Science Informatics Database (http://psi.nasa.gov/), which describes research previously conducted on the ISS, including that of the International Partners. A detailed catalog of previous, current, and proposed experiments, facilities and results, including investigator information, research summaries, operations, hardware information, and related publications is available at www.nasa.gov/iss-science through the NASA ISS Program Office. Additionally, details pertaining to research previously supported by the Space Life and Physical Sciences Research and Applications Division of NASA's Human Exploration and Operations Mission Directorate can be located in the Space Life & Physical Sciences Research and Applications Division Task Book in a searchable online database format at: https://taskbook.nasaprs.com/Publication/welcome.cfm. Please note that NRAs are in place for research to analyze previously-acquired data available in the PSI.

ISS U.S. National Laboratory

In 2011, NASA finalized a cooperative agreement with the Center for the Advancement of Science in Space to manage the International Space Station U.S. National Laboratory (ISS National Lab). The independent, nonprofit research management organization ensures the station's unique capabilities are available to the broadest possible cross section of U.S. scientific, technological and industrial communities.

The ISS National Lab develops and manages a varied research and development portfolio based on U.S. national needs for basic and applied research. It establishes a marketplace to facilitate matching research pathways with qualified funding sources and stimulates interest in using the national lab for research and technology demonstrations and as a platform for science, technology, engineering and mathematics education. The goal is to support, promote and accelerate innovations and new discoveries in science, engineering and technology that will improve life on Earth.

More information on ISS National Lab, including proposal announcements, is available at www.issnationallab.org.

Other Government Agencies

Potential funding for research on the ISS is also available via governmental partnerships with ISS U.S. National Laboratory and includes (but is not limited to) such government agencies as:

- Defense Agency Research Projects Agency (DARPA)
- Department of Energy (DOE)
- Department of Defense (DOD)
- National Science Foundation (NSF)
- National Institutes of Health (NIH)
- U.S. Department of Agriculture (USDA)

International Funding Sources

Unique and integral to the ISS are the partnerships established between the United States, Russia, Japan, Canada and Europe. All partners share in the greatest international project of all time, providing various research and experiment opportunities for all. These organizations – Japan Aerospace Exploration Agency (JAXA), Canadian Space Agency (CSA), ESA (European Space Agency), Russian space agency Roscosmos, Centre National d'Etudes Spatiales (CNES), and the German Aerospace Center (DLR) – provide potential funding opportunities for international scientists from many diverse disciplines.

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Acronyms

2D/3D	Two Dimensions, Two Dimensional/Three Dimensional
ACE-M	Advanced Colloids Experiment (Microscopy)
ACE-T	Advanced Colloids Experiment with sample Temperature control
BCAT	Binary Colloidal Alloy Tests
BDB	Buoyancy Dominated Boiling
CCF	Capillary Channel Flow
CFE	Capillary Flow Experiment
CHF	Critical Heat Flux
CL	Contact Line
CM-FV	Condensation Module-Flow Visualization
CM-HT	Condensation Module-Heat Transfer
CVB	Constrained Vapor Bubble
DEP	Dielectrophoretic
ECLSS	Environmental Control and Life Support Systems
EHD	Electrohydrodynamic
EXPRESS	EXpedite the PRocessing of Experiments to Space Station
FBCE	Flow Boiling and Condensation Experiment
FBM	Flow Boiling Module
FIR	Fluids Integrated Rack
FSLC	Freely Suspended Liquid Crystalline
GB	gigabyte(s)
ICF	Interior Corner Flow
ISS	International Space Station
LAD	Liquid Acquisition Device
LMM	Light Microscopy Module
MABE	Microheater Array Boiling Experiment
MAMS	Microgravity Acceleration Measurement System
MR	Magnetorheological
MSG	Microgravity Science Glovebox
NPBX	Nucleate Pool Boiling eXperiment
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
OASIS	Observation and Analysis of Smectic Islands in Space
PBE	Pool Boiling Experiments
PBRE	Packed Bed Reactor Experiment
PCS	Physics of Colloids in Space
PMD	Propellant Management Device
PI	Principal Investigator
RTD	Resistance Temperature Detector
SAMS	Space Acceleration Measurement System
SmA, SmC	Smectic A, Smectic C
TCCS	Trace Contaminant Control Subassembly
VG	Vane Gap
VTRE	Vented Tank Resupply Experiment
ZBOT	Zero Boil-Off Tank experiment

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