

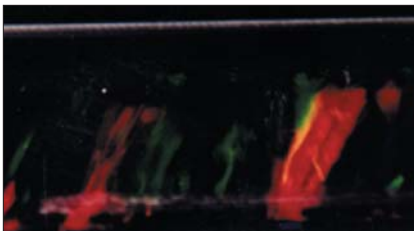
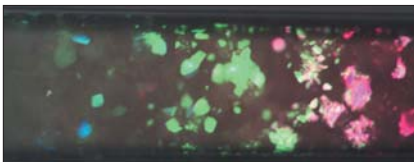
Going with the flow: Microgravity fluid physics

Most of the biological, environmental, and industrial processes required to support life take place in a fluid phase. Fluid motion accounts for most transport and mixing in natural and industrial processes as well as in living organisms. The ultimate goal of research in this area is to predict and even control this fluid behavior.

A detailed understanding of fluid dynamics over a broad range of length and time scales is essential for progress in many emerging research areas of physical and biological sciences. The low-gravity environment of space offers a unique opportunity for the study of fluid physics and transport phenomena, as the nearly weightless conditions allow researchers to observe and control fluid phenomena in ways that are not possible on Earth.

Experiments conducted in LEO have yielded rich results. Some were unexpected or could not be observed in Earth-based labs. These results have provided valuable insights into fundamental fluid behavior that apply to both terrestrial and space environ-

Monodisperse hard-sphere colloidal crystals were grown in space from a glass phase that does not crystallize on Earth (top). Binary colloidal crystals grown in space are much larger than their counterparts grown on Earth (bottom).



ments. Research on fluids management and heat transfer, in both propulsion and life-support systems, has contributed greatly to U.S. leadership in space exploration.

The National Research Council recently recommended that microgravity research to support technologies for human space exploration be given a high priority. And NASA has created a distinct enterprise, the Office of Biological and Physical Research, to conduct basic and applied research to support human space exploration by using the environment of space as a unique laboratory for the study of biological and physical processes.

There are currently five major research areas in OBPR's microgravity fluid physics program: complex fluids, multiphase flows and phase change, interfacial phenomena, biofluid mechanics, and dynamics and instabilities.

Complex fluids

Complex fluids comprise a large class of soft materials, often consisting of mesoscale supramolecular aggregates ranging in size from about 1 nm to roughly 1 μm . Their physical properties are determined by the interplay of entropic and structural intermolecular forces and interfacial interactions. Examples are microemulsions, foams and suspensions of colloids or microgels, liquid crystals, biological membranes, the intracellular macromolecular scaffolds of cytoskeleton, and the extracellular matrix.

This highly interdisciplinary field thus bridges the gap between synthetic and living materials. Although they pose scientific challenges, complex fluids have a broad range of industrial, biological, and environmental applications.

Researchers conducted a series of spaceflight experiments—Colloidal Dis-

order-Order Transition, Colloidal Gelation-2, and Physics of Hard Spheres—using photography, Bragg scattering, and light scattering to probe samples of hard sphere colloids and binary colloidal alloys. The experiments yielded the first-ever observation of dendritic growth in hard sphere colloids, and of the fact that colloidal samples that stay in glass phase (do not crystallize) in terrestrial conditions form crystals in a microgravity environment.

Colloidal crystals grown in microgravity initially showed a predominantly random, close-packed hexagonal structure that evolved to a face-centered cubic structure during long time periods. Colloidal crystals with dendritic morphologies are rarely observed in terrestrial experiments because of sedimentation. The suppression or near elimination of buoyancy in microgravity provides ideal conditions for colloidal dendrite growth.

Researchers performed the Mechanics of Granular Materials experiment to gain a quantitative understanding of the mechanical behavior of cohesionless granular materials under very low effective confining pressures/stresses. The purpose was to study the influence of particle interlocking and other fabric properties on the strength and behavior of the materials under such conditions.

In microgravity, granular materials exhibited strengths nearly 80% higher than conventional design and analysis concepts had predicted. Reexamination of existing theories in light of this observation is expected to yield improved theories for soil mechanics. The impact on foundation engineering could result in more effective designs and lower costs.

Multiphase flow and phase change

The Pool Boiling Experiment examined the fundamental mechanisms that constitute nucleate pool boiling, specifically its characteristics under the buoyancy-free conditions of microgravity. The experiments were part of a systematic theoretical and experi-

mental study of the heat transfer and vapor bubble dynamics associated with nucleation and bubble growth, departure, motion, collapse, and subsequent rewetting of a heated surface.

All high-heat-flux cases exhibited the expected boiling pattern; however, the low-heat-flux experiments produced results quite different from those found under terrestrial conditions, and also quite different from what one would have anticipated in microgravity. These differences were caused by the existence of a large vapor bubble attached to the heater surface. Within this bubble, small bubbles merged and subsequently condensed because of high subcooling. A thin layer of liquid persisted under the bubble, causing rewetting of the heater surface.

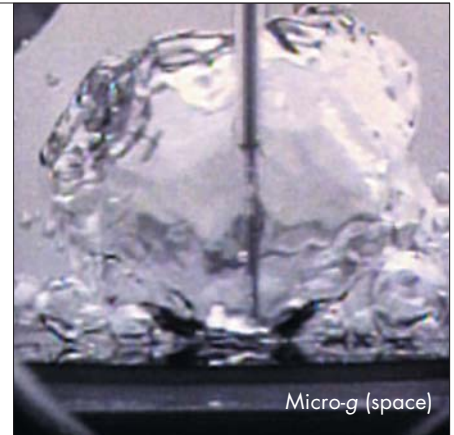
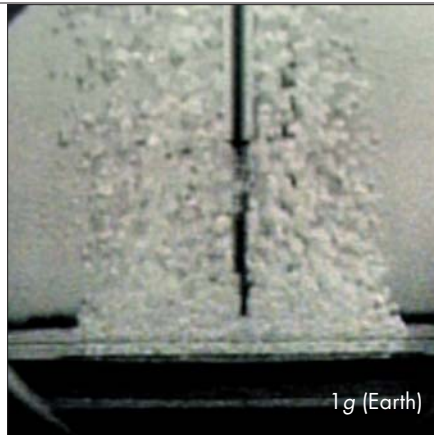
These results also indicated the potential for quasisteady nucleate pool boiling in long-term microgravity, with certain combinations of heat flux and bulk liquid subcooling. These simple experiments provided evidence that nucleate pool boiling may be achievable in a microgravity environment.

Flow regimes encountered in two-phase gas-liquid flows in microgravity are quite different from those in normal gravity. Tests conducted at NASA-Glenn in low-gravity aircraft and drop towers have provided a clear picture of flow regimes in microgravity, where three regimes are encountered: bubbly, slug, and annular-flow. Ground-based reduced-gravity data and modeling have also been used to develop a deterministic framework for specifying conditions under which flow regime transitions take place.

Interfacial phenomena

For certain geometrically constrained fluid configurations, unusual and counter-intuitive behavior was predicted mathematically but was not verifiable in terrestrial experiments. This was because of the dominant effect of hydrostatic forces on the free surface.

In the Angular Liquid Bridge and Interface Configuration Experiments, researchers observed how fluids in



A clear difference can be seen in the bubble size in pool boiling in the microgravity environment vs. normal gravity. On Earth, small bubbles rise from the heated surface because of buoyancy; in the near absence of buoyancy in microgravity, much larger bubbles are observed.

such constrained configurations behaved under reduced gravity. The experiments showed that theory could reliably be used to predict equilibrium configurations of liquid-vapor interfaces under microgravity conditions. They also verified the unusual behavior predicted by theory.

Experiments verified predictions of the mathematical model as follows: In a symmetrical vessel, a nonsymmetrical spoon-shaped interface was most stable, a saddle-shaped interface less stable, and a symmetric concave shape least stable. The results will serve to guide the use of mathematical and numerical techniques in predicting the configuration and stability of fluid interfaces in low-g environments.

Biofluid mechanics

Fluid flows and the transport of mass and heat occur in almost every biological process, from molecular and sub-cellular scales to whole systems. Human exposure to long-duration low-gravity environments is known to produce many undesirable physiological effects. Changes in vascular fluid distribution result quickly from the loss of hydrostatic pressure, and, on a longer time scale, from the shift of intercellular flows. Reduction of weight-bearing stress in microgravity induces bone loss and remodeling behavior. An adequate understanding of the underlying fluid physics and transport phenomena can provide new insight needed to develop effective countermeasures.

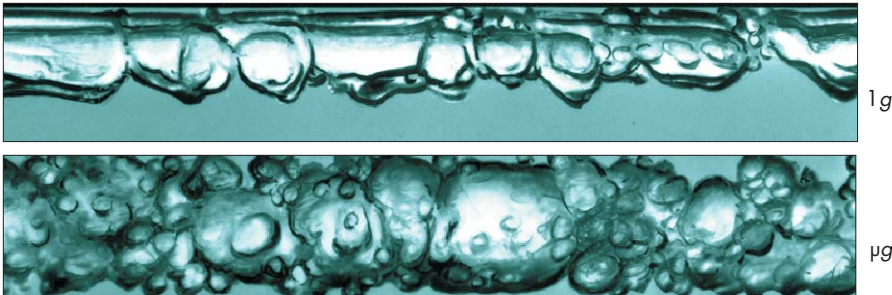
Research on the behavior of fluids and transport phenomena in weightlessness is also essential to the design and development of self-sustaining closed-loop systems required for hu-

man life support. Self-assembly at cellular levels also provides a pathway to nanotechnology.

The endothelial cell (EC) layer, which lines blood vessels from the aorta to the capillaries, provides the principal barrier to the transport of water and solutes between blood and underlying tissue. ECs are continuously exposed to the mechanical shearing force (shear stress) and normal force (pressure) imposed by flowing blood on their surfaces, and they are adapted to this mechanical environment.

In low gravity, the mechanical environment of ECs is perturbed drastically, and the transport properties of EC layers are altered in response. It is proposed that alterations in mechanical forces induced by microgravity, and their resultant influence on transendothelial transport of water and solute, are largely responsible for the characteristic cephalad fluid shift observed in humans experiencing low gravity. Understanding the mechanisms behind this fluid shift is crucial to developing countermeasures for crews facing long-duration exposure to low gravity.

Airways in lungs are liquid-lined, flexible tubes and can be subject to surface-tension instabilities that cause the liquid lining to form a plug. The plug obstructs the airway and reduces the ability to exchange gas. Airways closed by such plugs must be reopened, often by deep inspiration. The dynamics of liquid plug flow and rupture are being studied to determine their characteristics and how surfactants, airway flexibility, airway bifurcations, and other physiological effects influence them.



Differences in flow regimes for gas liquid two-phase flows in normal gravity and microgravity are apparent. Stratified flow observed in normal gravity is absent in microgravity. Light regions represent gas, and darker regions represent the liquid phase.

Dynamics and instabilities

Ground-based researchers have reported the first-ever experimental observation of long-wavelength instability in investigations using very thin liquid layers where the effect of gravity is negligible. The short-wavelength instability results in formation of well-known hexagonal cells. Although this long-wavelength instability was predicted 35 years ago, it had not been observed. Researchers have also developed a numerical simulation whose results are in qualitative agreement with experimental observations. This instability could become the primary one in a microgravity environment.

The Surface Tension Driven Convection Experiment (STDCE) flew on two shuttle flights (USML-1 and -2). The experiment was designed to study the nature and extent of steady and oscillatory thermocapillary flows in the absence of buoyancy-driven convective contributions. Because of the unique nature of the microgravity environment, this was the first time that a high Marangoni number (zero Rayleigh number) calculation could be compared to a high Marangoni number experiment.

Surprisingly, no oscillatory flow was observed, even for Marangoni numbers as high as 10^5 . The STDCE-2 data (together with ground-based results) show that the value of the Marangoni number at the onset of oscillations varies with the container size. These results also confirmed that the Marangoni number alone does not determine the onset. The importance of surface deformation and its relationship to the transition to oscillatory flow was also demonstrated.

The Geophysical Fluid Flow Cell experiment investigated the fluid dynamics of buoyancy-driven circulation in rotating spherical shells and was conducted on the Second U.S. Microgravity Laboratory, or USML-2. Among the findings was the existence of multiple latitudinal jets with motion of thermal waves in the same sense as the basic rotation at low and high latitudes (prograde rotation) and retrograde pattern rotation at mid-latitude. These results (not previously predicted by computational models) provide an alternative view of the mechanisms for "banded" structures observed in planetary atmospheres. The results also showed that long-time evolution of modestly convecting flows in slowly rotating spherical shells (such as Earth's mantle) is not unique, but depends upon initial conditions.

Space station facilities

Fluid physics and transport phenomena studies on the ISS will be carried out in the Fluids Integrated Rack (FIR), Microgravity Science Glovebox, and EXPRESS racks. By providing a diverse set of terrestrial lab-like features, FIR will reduce costs, allowing NASA to conduct more investigations.

The FIR is a modular, multiuser research facility in Destiny, the U.S. lab module. It is configured to accommodate a broad range of experiments in fluid physics but is flexible enough to serve other science disciplines as well. It is being designed for autonomous and remote control operations, primarily through the Telescience Support Center at NASA-Glenn.

The first FIR payload, the Light Microscopy Module, offers a suite of

state-of-the-art diagnostics techniques used by physical and biological scientists in ground-based labs. Its diagnostic capabilities include video microscopy to observe sample features including basic structures and dynamics, thin film interferometry, laser tweezers for colloidal particle manipulation and patterning, confocal microscopy to provide enhanced 3D visualization of colloidal structures, and spectrophotometry to measure colloidal crystal photonic properties. In addition to using the confocal system, biological researchers can conduct fluorescence imaging by using the fiber-coupled output of an Nd:YAG laser operating at 532 nm, the 437-nm line of a mercury arc, or appropriate narrow-band filtering of a metal halide white light source.

A fluid future

Fluid mechanics and thermal sciences provide the underpinning for most of the scientific inquiry in space and for development of mission-enabling and enhancing technologies. Thus the Fluid Physics and Transport Phenomena Program is poised not only to generate knowledge bases for emerging new technologies but also to invigorate the more traditional ones. Research in these diverse areas will extend the knowledge bases necessary for realizing mission-critical technologies. This work will also enable improvements in the efficiency and effectiveness of terrestrial processes, both man-made and natural.

Constraints on the operation of life-support and power systems on long-duration space missions necessitate development of efficient, self-sustaining systems. Knowledge gained from their development will have direct relevance to terrestrial systems, allowing either improvement of existing technology or replacement of older technologies with new, more efficient ones, offering great promise for our future in space and on Earth.

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