

Gravitational and Space Research

Transport Phenomena Research in Microgravity via the ISS National Lab to Benefit Life on Earth

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Abstract

The International Space Station (ISS) National Laboratory provides an ideal platform in persistent microgravity to conduct research in the absence of gravity-induced phenomena (e.g., buoyancy-driven convection and sedimentation), enabling opportunities for breakthrough science. Since 2016, the U.S. National Science Foundation (NSF) Chemical, Bioengineering, Environmental, and Transport Systems (CBET) Division has partnered with the Center for the Advancement of Science in Space™ (CASIS™), manager of the ISS National Lab, to release an annual joint solicitation in transport phenomena research on the ISS to benefit life on Earth. To date, the NSF-CASIS partnership has yielded 37 NSF-funded research investigations sponsored by the ISS National Lab. This paper highlights a few of the important scientific discoveries that have resulted from the fruitful NSF-CASIS collaboration and offers insight into the importance of expanding collaborations between government agencies to increase access to space and enable groundbreaking research that benefits humanity. Research areas explored include biophysics, combustion, complex fluids, fluid dynamics, heat transfer and multiphase flow, and materials science.

Keywords

combustion • complex fluids • fluid dynamics • heat transfer • materials science • biophysics

Introduction

For 9 consecutive years (since 2016) the Chemical, Bioengineering, Environmental, and Transport Systems (CBET) Division of the U.S. National Science Foundation's (NSF) Engineering Directorate has partnered with the Center for the Advancement of Science in Space™ (CASIS™), manager of the International Space Station (ISS) National Laboratory, to release an annual joint solicitation for microgravity research in transport phenomena on the ISS to benefit life on Earth. In this work, we present an overview of the NSF-CASIS collaboration in transport phenomena with three objectives: 1) to offer insight into the immense possibilities enabled by microgravity research, 2) to highlight important research findings that have resulted from the fruitful NSF-CASIS collaboration, and 3) to highlight the importance of U.S. government interagency collaborations to increase access to space and enable groundbreaking research and technology development.

Research in microgravity enables the study of fundamental physical phenomena that are not attainable, or are obscured, on Earth due to gravity-driven forces such as buoyancy-induced convection or density-driven segregation. This is particularly true when considering the study of transport phenomena (e.g., fundamental fundamental heat, mass, and

momentum transfer), in which buoyancy-induced convection and sedimentation are typically dominant factors. In microgravity, these gravity-driven phenomena are greatly reduced, or even negligible, enabling the study of underlying phenomena such as surface tension (e.g., Marangoni convection and capillary flows) and diffusion (e.g., mass diffusion, Brownian motion, thermophoresis, and dielectrophoresis). For example, the absence of sedimentation in complex fluids allows researchers to investigate their physical properties and formation under a new range of intramolecular forces and interfacial interactions. In combustion systems, researchers can study chemical kinetics, soot formation, and flame evolution in the absence of buoyancy-enhanced mixing, enabling the investigation of combustion phenomena at longer residence times and under conditions in which diffusion is the dominant transport mechanism in lieu of convection.

There are several different platforms that provide microgravity conditions for research investigations. Drop towers offer short-duration microgravity ($\sim 10^{-5}$ g for typically 5.2 s or less). Parabolic flights can offer microgravity ($\sim 10^{-2}$ g) for up to 25 s but are susceptible to disturbances such as G-jitter (Thomas et al., 2000). Suborbital vehicles can carry research investigations to altitudes above the Karman Line and provide approximately 3 min of microgravity ($\sim 10^{-4}$ g) (Wagner, 2021 and Ferranti

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et al., 2021). The ISS, on the other hand, offers persistent microgravity ($\sim 10^{-6}$) in a near-quiescent environment in low Earth orbit (LEO). The long-duration microgravity provided by the ISS is crucial for scientific investigations in which the relevant timescales of the phenomena are too long to be observed using short-duration microgravity platforms (Rojas-Alva and Jomaas, 2022), which is often the case for fundamental transport phenomena.

To date, the first eight NSF-CASIS joint solicitations in transport phenomena research on the ISS to benefit life on Earth have yielded 37 NSF-funded research investigations. The specific focus area(s) of the solicitation have evolved over the years,

ranging from fluid dynamics to combustion and thermal transport processes to the current focus areas of transport phenomena and nanoscale interactions, which cover the research areas of all programs under the Transport Phenomena Cluster (i.e., Fluid Dynamics, Particulate and Multiphase Processes, Combustion and Fire Systems, and Thermal Transport Processes) and the Nanoscale Interactions program of the NSF CBET Division. The projects that have been awarded through these funding opportunities are listed in Table 1. Additional information can be found on the NSF website.

The strategic priorities of the ISS National Lab intersect with those of the NSF in their goal to “promote the progress

Table 1. NSF-funded research projects that have resulted from the NSF-CASIS joint solicitation for microgravity research in transport phenomena on the ISS to benefit life on Earth. Projects with multiple principal investigators (PIs) are collaborative projects. The PI institution is the PI's institution at the time of award.

No.	Year Awarded	Project Title	PI Name(s)	PI Institution
1	2016	ISS: Quantifying Cohesive Sediment Dynamics for Advanced Environmental Modeling	Paolo Luzzatto-Fegiz, Eckart Meiburg	University of California, Santa Barbara
2	2016	ISS: Unmasking contact-line mobility for Inertial Spreading using Drop Vibration and Coalescence	Susan Daniel (Former PI: Paul Steen)	Cornell University
3	2016	ISS: Kinetics of nanoparticle self-assembly in directing fields	Eric Furst	University of Delaware
4	2016	ISS: Inertial Spreading and Imbibition of a Liquid Drop Through a Porous Surface	Michel Louge, Olivier Desjardins	Cornell University
5	2016	ISS: Constrained Vapor Bubbles of Ideal Mixtures	Joel Plawsky	Rensselaer Polytechnic Institute
6	2017	ISS: Collaborative Research: Spherical Cool Diffusion Flames Burning Gaseous Fuels	Peter Sunderland	University of Maryland, College Park
			Richard Axelbaum	Washington University in St. Louis
			Forman Williams	University of California, San Diego
7	2017	ISS: Collaborative Research: Thermally activated directional mobility of vapor bubbles in microgravity using microstructured surfaces	Sushil Bhavnani	University of California, Davis
			Vinod Narayanan	Auburn University
8	2017	ISS: Flame Spread in Confined Spaces - Study of the Interactions between Flame and Surrounding Walls	Ya-Ting Liao, Paul Ferkul	Case Western Reserve University
9	2018	ISS: GOALI: Nonequilibrium Processing of Particle Suspensions with Thermal and Electrical Field Gradients	Boris Khusid, Alton Reich, Lou Kondic	New Jersey Institute of Technology
			Paul Chaikin, Andrew Hollingsworth	New York University
10	2019	ISS: Collaborative Research: Interfacial bioprocessing of pharmaceuticals via the Ring-Sheared Drop (RSD) module aboard ISS	Amir Hirs	Rensselaer Polytechnic Institute
			Juan Lopez	Arizona State University
11	2019	ISS: Collaborative Research: Examination of the Multi-physical Properties of Microgravity-synthesized Graphene Aerogels	Debbie Senesky	Stanford University
			Roya Maboudian, Carlo Carraro	University of California, Berkeley
12	2019	ISS: A Microgravity Microfluidic Study of Packing and Particle Stabilization of Foams and Emulsions	Jing Fan, Charles Maldarelli	CUNY, The City College of New York
13	2020	ISS: A new paradigm for explaining catastrophic post-wildfire mudflows: transport phenomena and gravity-driven aggregation dynamics of hydrophobic particle-air-water mixtures	Ingrid Tomac	University of California, San Diego
14	2020	ISS: Synthesis of Electrically Conductive High-Temperature Composites Under Microgravity and Normal Gravity Conditions	Kathy Lu	Virginia Polytechnic Institute and State University
15	2020	ISS: Gravitational Effects on the Faraday Instability	Ranga Narayanan	University of Florida
16	2020	ISS: Dynamic Manipulation of Multi-Phase Flow Using Light-Responsive Surfactants for Phase-Change Applications	Yangying Zhu, Javier Read de Alaniz, Paolo Luzzatto-Fegiz	University of California, Santa Barbara

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No.	Year Awarded	Project Title	PI Name(s)	PI Institution
17	2020	ISS: Collaborative Research: Bimodal Colloidal Assembly, Coarsening and Failure: Decoupling Sedimentation and Particle Size Effects	Safa Jamali	Northeastern University
			Ali Mohraz	University of California, Irvine
18	2021	ISS: Collaborative Research: Individual and Collective Behavior of Active Colloids in Microgravity	Alicia Boymelgreen	Florida International University
			Jarrod Schiffbauer	Colorado Mesa University
19	2021	ISS: Thermophoresis in quiescent non-Newtonian fluids for bioseparations	James Gilchrist, Xuanhong Cheng, Kelly Schultz	Lehigh University
20	2021	ISS: Understanding the Gravity Effect on Flow Boiling Through High-Resolution Experiments and Machine Learning	Chen Li, Yan Tong	University of South Carolina at Columbia
21	2021	Collaborative Research: ISS: GOALI: Transients and Instabilities in Flow Boiling and Condensation Under Microgravity	Joel Plawsky, Corey Woodcock	Rensselaer Polytechnic Institute
			Boris Khusid, Thomas Conboy	New Jersey Institute of Technology
22	2021	ISS: Wicking in gel-coated tubes	Emilie Dressaire	University of California, Santa Barbara
23	2021	ISS: Flame Spread Response to Non-steady Airflow	James Urban	Worcester Polytechnic Institute
24	2022	Collaborative Research: ISS: Assessing the Effect of Microgravity on Growth and Properties of Metal-Organic Framework (MOF) Crystals	Debbie Senesky	Stanford University
			Roya Maboudian, Carlo Carraro	University of California, Berkeley
25	2022	ISS: Plasmonic Bubble Enabled Nanoparticle Deposition under Micro-Gravity	Tengfei Luo	University of Notre Dame
26	2022	Collaborative Research: ISS: Revealing interfacial stability, thermal transport and transient effects in film evaporation in microgravity	James Hermanson	University of Washington
			Aneet Dharmavaram Narendranath, Jeffrey Allen	Michigan Technological University
27	2022	Collaborative Research: ISS: Microgravity enabled studies of particle adsorption dynamics at fluid interfaces	Joelle Frechette	University of California, Berkeley
			Michael Bevan	Johns Hopkins University
28	2022	ISS: Uncovering transient dynamics and equilibrium states of particle aggregates in fluids	Raul Cal	Portland State University
29	2022	Collaborative Research: ISS: Biofilm Inhibition with Germicidal Light Side-Emitted from Nano-enabled Flexible Optical Fibers in Water Systems	Paul Westerhoff, Jennifer Barrila, Cheryl Nickerson, Francois Perreault	Arizona State University
			Robert McLean	Texas State University, San Marcos
30	2022	ISS: Transient Behavior of Flow Condensation and Its Impacts on Condensation Rate	Chen Li, Yan Tong	University of South Carolina at Columbia
31	2022	ISS: Active Liquid-Liquid Phase Separation in Microgravity	Zvonimir Dogic	University of California, Santa Barbara
32	2023	Collaborative Research: ISS: Probing Interfacial Instabilities in Flow Boiling and Condensation via Acoustic Signatures in Microgravity	Ying Sun, Ahmed Allam, Yongfeng Xu	University of Cincinnati
			Han Hu	University of Arkansas
33	2023	Collaborative Research: ISS: Colloidal Microflyers: Observation and Characterization of (Self-) Thermophoresis through Air in Microgravity	Jeffrey Moran	George Mason University
			David Warsinger	Purdue University
34	2023	ISS: Protein flow and gelation in the absence of solid-wall nucleation	Amir Hirs, Patrick Underhill	Rensselaer Polytechnic Institute
35	2023	Collaborative Research: ISS: Understanding thermal transport across a condensing film by conducting experiments in microgravity	Chirag Kharangate	Case Western Reserve University
			Kuan-Lin Lee, Josh Charles	Advanced Cooling Technologies, Inc.
36	2023	ISS: Biofilm growth and architecture in porous media: exploring the effect of gravitational and interfacial forces on biofilm growth patterns	Dorthe Wildenschild, Tala Navab-Daneshmand	Oregon State University
37	2023	ISS: The Influence of Microgravity on Bacterial Transport and Pellicle Morphogenesis	Howard Stone	Princeton University



Figure 1. Photograph of the International Space Station. Image courtesy of NASA

of science” and “advance the national health, prosperity and welfare,” or in brief, to benefit life on Earth. The ISS, shown in Figure 1, is at the center of this intersection as an unprecedented international engineering feat that enables researchers to study phenomena not attainable on Earth that can lead to groundbreaking scientific advances. According to the National Aeronautics and Space Administration’s (NASA) 2023 Annual Highlight of Results from the International Space Station, the ISS has hosted more than 3,300 research investigations from researchers in over 100 countries, leading to more than 4,000 publications.

Through the ISS National Lab, researchers have access to multiple research facilities and supporting flight hardware onboard the ISS, including commercial platforms and facilities maintained by NASA and its international partners. In most cases, experiments are tailored to fit the design and operational capabilities of existing facilities. However, in some cases, these research facilities can be modified to accommodate some needs of the proposed experiment. The NSF and CASIS have awarded funding and ISS resources for transport phenomena investigations over a wide range of research areas, including biophysics, combustion, complex fluids, fluid dynamics, heat transfer and multiphase flow, and materials science. This paper will highlight some of the most impactful investigations that have been enabled by the NSF-CASIS joint solicitation for transport phenomena research on the ISS to benefit life on Earth, describe several ongoing investigations, and discuss the future of ISS National Lab-sponsored research.

Combustion

The lack of buoyancy-enhanced convection in the prolonged microgravity environment of the ISS operating in LEO has led

to significant advances in fundamental combustion research. The microgravity environment has been particularly valuable for non-premixed flames that on Earth would rely heavily on buoyancy-enhanced convection to supply the ambient reactant to the flame. In microgravity, however, the dominant mechanism of transport for the ambient reactant is diffusion. This includes candle flames (Dietrich et al., 2000), spherical diffusion flames (Irace et al., 2021), droplet flames (Dietrich et al., 2014), gas-jet flames (Diez et al., 2009), confined flames of solid fuels (Li et al., 2021), and flat flames (Dehghani et al., 2023). The much longer timescales for diffusion, when compared with buoyancy-enhanced convection, make persistent microgravity essential for studying these phenomena. For example, it was recently shown that spherical diffusion flames in microgravity may take on the order of 100,000 s (i.e., over 1 day) to effectively asymptote to steady state (Irace et al., 2023a). Other important combustion areas that have been studied in microgravity include flame balls (Ronney, 1998), coflow flames (Giassi et al., 2016), and flames with an applied electric field (Chien et al. 2022). The results of these studies have led to significant advances in our understanding of soot formation, radiation heat transfer, wildfires, flame-spread in buildings, oxygen-enriched combustion for carbon capture and storage, combustion chemistry, flammability limits, and many more fundamental combustion phenomena that are critical for everyday life on Earth. Two combustion experiments have been supported through the NSF-CASIS collaboration, and both have yielded promising fundamental discoveries and results that substantially impacted their fields of investigation.

Spherical Cool Diffusion Flames Burning Gaseous Fuels

Kim et al. (2023) recently observed the *first-ever spherical cool diffusion flame burning gases* using NASA’s Advanced Combustion via Microgravity Experiments (ACME) chamber insert in the Combustion Integrated Rack (CIR) onboard the ISS (Kim et al., 2023). The flames, shown in Figure 2, were gaseous burner-supported spherical diffusion flames. The burner was a 6.35 cm diameter porous stainless-steel sphere. The reactant mixtures for the cool flames were a 30% n-butane/70% nitrogen mixture by volume as the fuel emanating from the burner and a 39% oxygen/61% nitrogen mixture by volume as the ambient oxidizer. The hydrocarbon mass flow rate ranged from 0.75 to 1.5 mg/s. The pressure was 2 bar. Additional conditions that were investigated included fuels of ethane and propane, inverse flames (i.e., oxidizer emanating from the burner into an ambient fuel), various pressures, a wide range of flow rates, and a wide range of fuel and oxidizer concentrations. However, the cool flames were not readily produceable and were only observed within the narrow range of conditions described above.

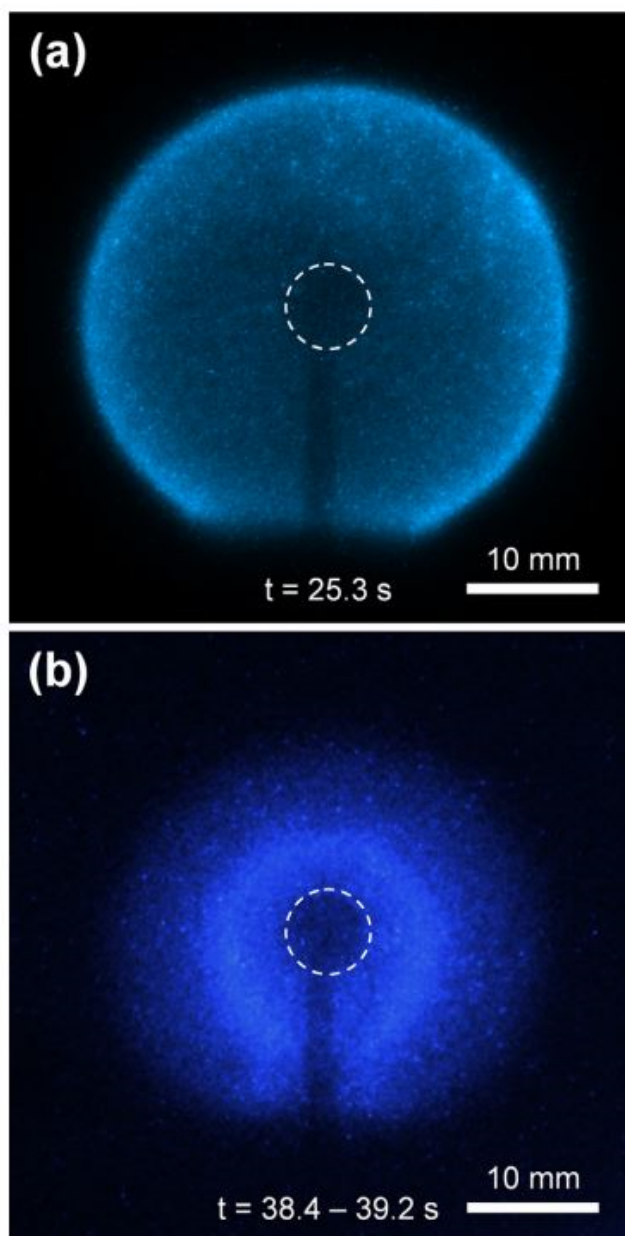


Figure 2. Intensified camera images of (a) a hot flame and (b) a cool flame. Figure recreated from Kim et al. (2023). Reprinted from Proceedings of the Combustion Institute, 39(2), Minhyeng Kim, Kendyl A. Waddell, Peter B. Sunderland, Vedha Nayagam, Dennis P. Stocker, Daniel L. Dietrich, Yiguang Ju, Forman A. Williams, Phillip Irace, and Richard L. Axelbaum, Spherical gas-fueled cool diffusion flames, 1647-1656, Copyright (2023), with permission from Elsevier.

The flow rate of the burner reactant was held constant for the duration of each test. A hot flame was ignited and then allowed to radiatively extinguish, as in Irace et al. (2023b). After the hot flame radiatively extinguished, the flow from the burner continued for at least 10 s to allow for the possible

ignition of a cool flame. Using this procedure, 15 such cool flames spontaneously ignited after radiative extinction of their hot flame counterpart. The cool flames were imaged using an intensified camera, and the radiant emission was measured using a radiometer. The cool flames could not be detected in real-time because they could not be seen in the video of the operation, and the measured data were not available until later (Kim et al., 2023).

Kim et al. (2023) were able to develop an analytical model based on the Spalding model of droplet combustion and the partial burning regime, which illustrated the importance of the effect of burner temperature on the cool flames and allowed them to predict the cool flame location (Kim et al., 2023). These spherical gaseous cool diffusion flames would not be attainable on Earth due to buoyancy-enhanced convection accelerating the flow field, which would yield a non-spherical flame, enhance mixing, and significantly reduce the residence time, leading to a hot flame. Their findings have important implications for improving the current understanding of cool flame chemistry, which could lead to increased efficiency in internal combustion engines on Earth.

Study of the Interactions Between Flames and Surrounding Walls

Li et al. (2021) studied the spread of concurrent flow confined flames using the Burning and Suppression of Solids (BASS) hardware in the Microgravity Science Glovebox (MSG) on the ISS (Li et al., 2021). Persistent microgravity onboard the ISS allowed them to isolate the effects of imposed concurrent flow in the absence of buoyancy-induced convection. They tested materials (i.e., solid fuels) that included SIBAL fabric (a composite cotton-fiberglass fabric blend) and 1-mm thick polymethyl methacrylate (PMMA) slabs. The flow duct velocity ranged from 3 to 32 cm/s. Three types of baffles (transparent polycarbonate, anodized black aluminum, and polished aluminum) were used to investigate the effects of altering radiation heat transfer conditions at the boundary. The baffle distances ranged from 2 to 5 cm (Li et al., 2021).

Li et al. (2021) found that for low flow speeds (less than 17 cm/s) and all baffle types, steady-state flame spread is achieved with a limiting flame length and constant spread rate. For high flow speeds, the flame continuously grows, except when the baffle distance is near the quenching distance. Furthermore, they were able to validate a previous hypothesis that the optimal baffle distance for a high flame spread rate and long flame length is 4 cm, as shown in the steady flame profiles at different confined conditions in Figure 3. The optimal baffle distance is hypothesized to be a result of flow acceleration during combustion, heat loss to the baffles, and limited oxygen. At smaller baffle distances, the flame is starved of oxygen and suffers from additional heat loss to the baffles. At larger baffle distances, the radiative properties of

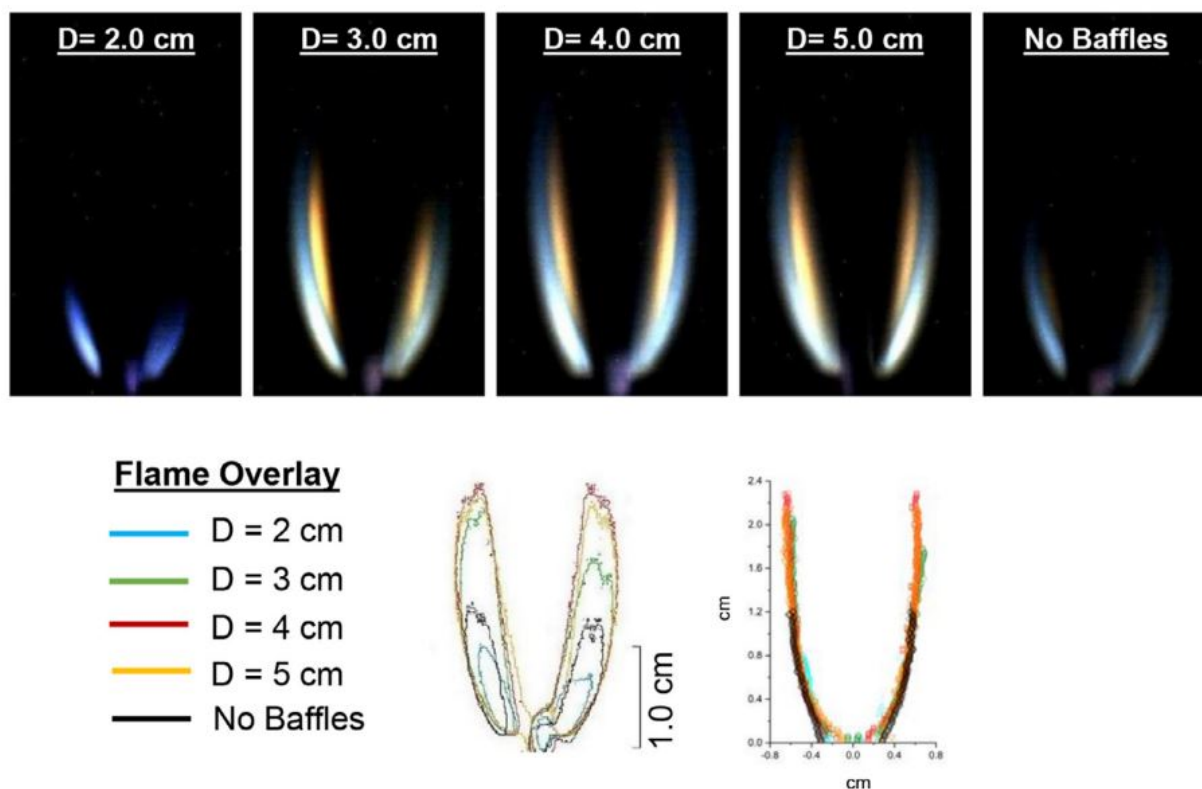


Figure 3. (Top) Comparison of steady flame profiles at different confined flame conditions using black anodized aluminum baffles or no baffles, with a flow speed of 6 cm/s. When there is no baffle, the flame is situated between a transparent polycarbonate window and a black duct wall on the right and left side of a flame, as imaged, respectively. **(Bottom)** Overlaid profiles of the outer edge and center profile for each of the five flames. This figure is recreated from Li et al. (2021). Reprinted from Combustion and Flame, 227, Li Yanjun, Liao Ya-Ting T., Paul V. Ferkul, Michael C. Johnston, and Charles Bunnell, Experimental study of concurrent-flow flame spread over thin solids in confined space in microgravity, 39-51, Copyright (2021), with permission from Elsevier.

the flame are less impacted by the baffles, and the confinement mainly affects the flame through thermal expansion during combustion (Li et al., 2021).

Regarding the impact of different baffle types on the flame, results show that aluminum baffles result in the strongest flame and transparent baffles result in the weakest flame due to optical effects on radiation heat transfer (Li et al., 2021).

Li et al. (2021) were able to use these experimental results to validate a numerical model. Their conclusions and numerical model have important implications for understanding flame spread, with applications in building fire safety on Earth and spacecraft fire safety.

Heat Transfer and Multiphase Flow

Microgravity also enables the study of critical heat transfer phenomena, such as Marangoni flow (i.e., thermo-capillary convection) and transients/instabilities in multiphase flows (i.e., boiling and condensation), that are typically masked

or obscured by buoyancy-induced flows in a normal gravity environment. These phenomena are important for obtaining a comprehensive understanding of heat exchangers on Earth and in space. These studies have often focused on multi-phase phenomena such as boiling and condensation in passive and active cooling devices. Researchers have studied flow boiling to validate models for critical heat flux (CHF) in microgravity (Mudawar et al., 2024) and flow condensation to improve condenser efficiencies on Earth. Investigators have also used heat pipes to improve our fundamental understanding of the physics of evaporation and condensation and how they affect cooling processes in space (Yu et al., 2022). Studying heat transfer phenomena in microgravity also has benefits for understanding the spacecraft thermal protection systems needed to enable deep-space exploration.

Thermally Activated Directional Mobility of Vapor Bubbles

Sridhar et al. (2024) took advantage of the lack of buoyancy in microgravity to study vapor bubble dynamics on flat and micro-structured surfaces for applications to delay dryout in

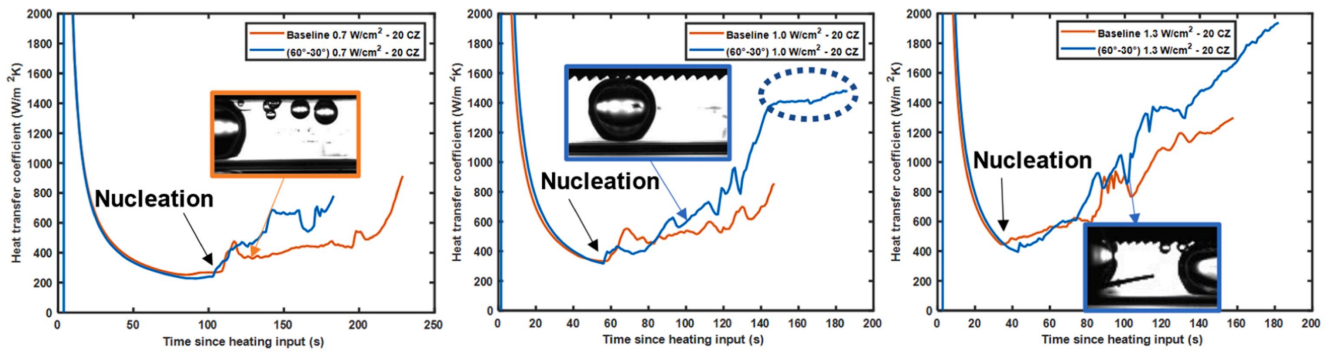


Figure 4. Heat transfer coefficient as a function of time for the sawtooth microstructure (blue) and flat baseline (orange) surfaces at various heat fluxes. The applied heat fluxes are 0.7 W/cm² (left), 1.0 W/cm² (center), and 1.3 W/cm² (right). The inset images show high-speed image frames captured during the experiment. The nearly constant heat transfer coefficient circled at the end of the sawtooth microstructure experiment at 1.0 W/cm² is due to the constant temperature difference maintained between the surface and the fluid. Figure reproduced from Sridhar et al. (2024). Reprinted from International Journal of Heat and Mass Transfer, 222, Karthekeyan Sridhar, Vinod Narayanan, and Sushil H. Bhavnani, Enhanced heat transfer in microgravity from asymmetric sawtooth microstructure with engineered cavities, 125158, Copyright (2024), with permission from Elsevier.

heat exchangers and improve heat transfer in multiphase flows (Sridhar et al., 2024). The flat baseline surface was additively manufactured Ti-6Al-4V, and the micro-structured surface was a 60°–30° asymmetric sawtooth structure. Both surfaces had 250- μ m square cavities to provide nucleation sites. The fluid investigated was a perfluorocarbon fluid (FC-72).

The microgravity experiments were conducted using a modified version of NASA's Pore Formation and Mobility Investigation (PFMI) facility. The fluid was contained in sealed ampoules with a nichrome coating on one side to provide heat input. Both surfaces were seen to trigger more nucleation sites as the applied heat flux was increased. As vapor bubbles grew on the flat baseline surface, they remained stationary. By contrast, vapor bubbles that grew on the sawtooth microstructured surface departed when they reached a critical mobility diameter and began to move across the crests of the sawteeth due to liquid pockets across the troughs that enable movement. It was found that the critical vapor bubble mobility diameter increased with increasing heat flux input for the range of low heat fluxes attempted (Sridhar et al., 2023).

Figure 4 shows the heat transfer coefficient as a function of time for applied heat fluxes of 0.7, 1.0, and 1.3 W/cm² in microgravity for both surfaces. As the experiment is initiated, the heat transfer coefficient on both surfaces is comparable. After nucleation begins, the heat transfer coefficient for each surface increases with time for all applied heat fluxes. However, the heat transfer coefficient of the microstructure surface eventually surpasses that of the baseline (Sridhar et al., 2024).

When the constant heat flux is applied, the change in heat transfer characteristics is dictated by the vapor bubble dynamics. For the microstructure surface, the nucleated bubbles grow and coalesce with neighboring bubbles but continue to move across the microstructure surface due to the

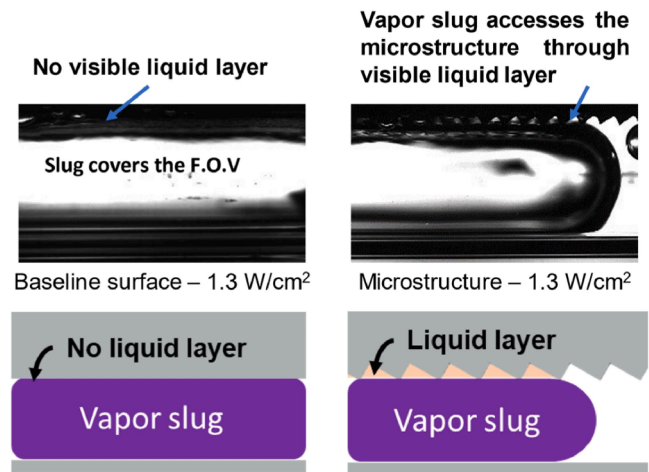


Figure 5. A comparison of the vapor slug dynamics on the flat baseline surface (left) and the 60°–30° sawtooth microstructure surface (right) in microgravity at a heat flux of 1.3W/cm². For the flat surface, the vapor slug covers the entire field of view, and no liquid layer is visible between the slug and the surface. For the sawtooth microstructure surface, there is a visible liquid microlayer across the crests of the sawteeth. The liquid layer is highlighted in the sawtooth microstructure schematic (bottom-right). Figure reproduced from Sridhar et al. (2024). Reprinted from International Journal of Heat and Mass Transfer, 222, Karthekeyan Sridhar, Vinod Narayanan, and Sushil H. Bhavnani, Enhanced heat transfer in microgravity from asymmetric sawtooth microstructure with engineered cavities, 125158, Copyright (2024), with permission from Elsevier.

liquid layer provided by the sawteeth troughs. The flat baseline surface, in contrast, does not have a visible liquid layer. The liquid film dynamics beneath the vapor slugs, illustrated in Figure 5, are found to substantially influence heat transfer and are the primary reason for the superior performance of the

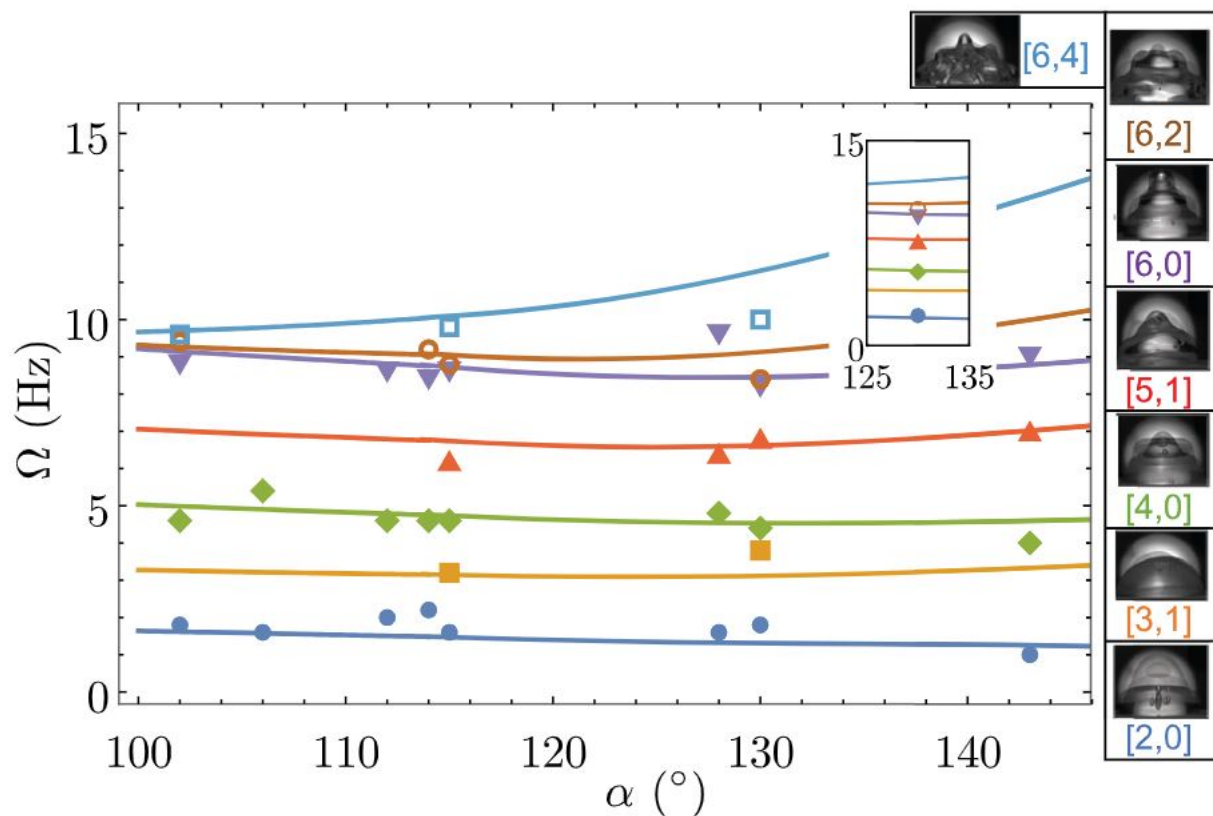


Figure 6. Frequency as a function of static contact angle α ($^\circ$) for several modes and substrates in microgravity. Experimental measurements are denoted by symbols, and theoretical predictions with free contact lines $\Lambda = 0$ are denoted by solid lines, where Λ is the mobility. The inset plot is the frequency for substrate P1 with pinned contact line $\Lambda = \infty$ (see McCraney et al., 2022b). The experimental error is ± 0.2 Hz, denoted by the symbol size. Reprinted figure with permission from J. McCraney, V. Kern, J.B. Bostwick, S. Daniel, and P.H. Steen, *Physical Review Letters*, 129, 084501, 2022. Copyright (2022) by the American Physical Society.

sawtooth microstructure surface relative to the flat baseline surface (Sridhar et al., 2024).

Earth-based experiments were conducted using the same surfaces but in an inverted gravity (i.e., downward-facing) orientation. The flat surface produced a vapor slug that covered the heated area, whereas the micro-structured surface resulted in the organized movement of discrete vapor slugs across the surface (Sridhar et al., 2023). Overall, the results of this work enhance our understanding of vapor mobility and heat transfer on Earth, and also show promise in enabling two-phase high heat flux dissipation for electronics in microgravity.

Fluid Dynamics

The study of fluid dynamics in microgravity, where buoyancy is nearly absent and the importance of interfacial or capillary forces increases (Motil et al., 2020), can yield an improved fundamental understanding for the modeling of fluid dynamics

for several applications on Earth. Some examples include the stability of Marangoni flows, crystal growth, the production of materials, energy generation applications, thermal management technologies, blood flow, and several other life science applications (McCraney et al., 2022a). Furthermore, an improved understanding of capillary flows in microgravity is critical for space applications such as liquid storage systems, thermal control systems, life-support systems, and fluid materials processing (Weislogel et al. 2009).

Unmasking Contact-Line Mobility for Inertial Spreading Using Drop Vibration

A team from Cornell University used the persistent microgravity environment onboard the ISS to study inertial spreading, which is important for manufacturing, coating, and forming operations on Earth. The investigation was split into two experimental setups, both of which were conducted in NASA's Observation and Analysis of Smectic Islands in Space (OASIS) bubble chamber hardware. The first setup used a mechanical wave driver that drove normal

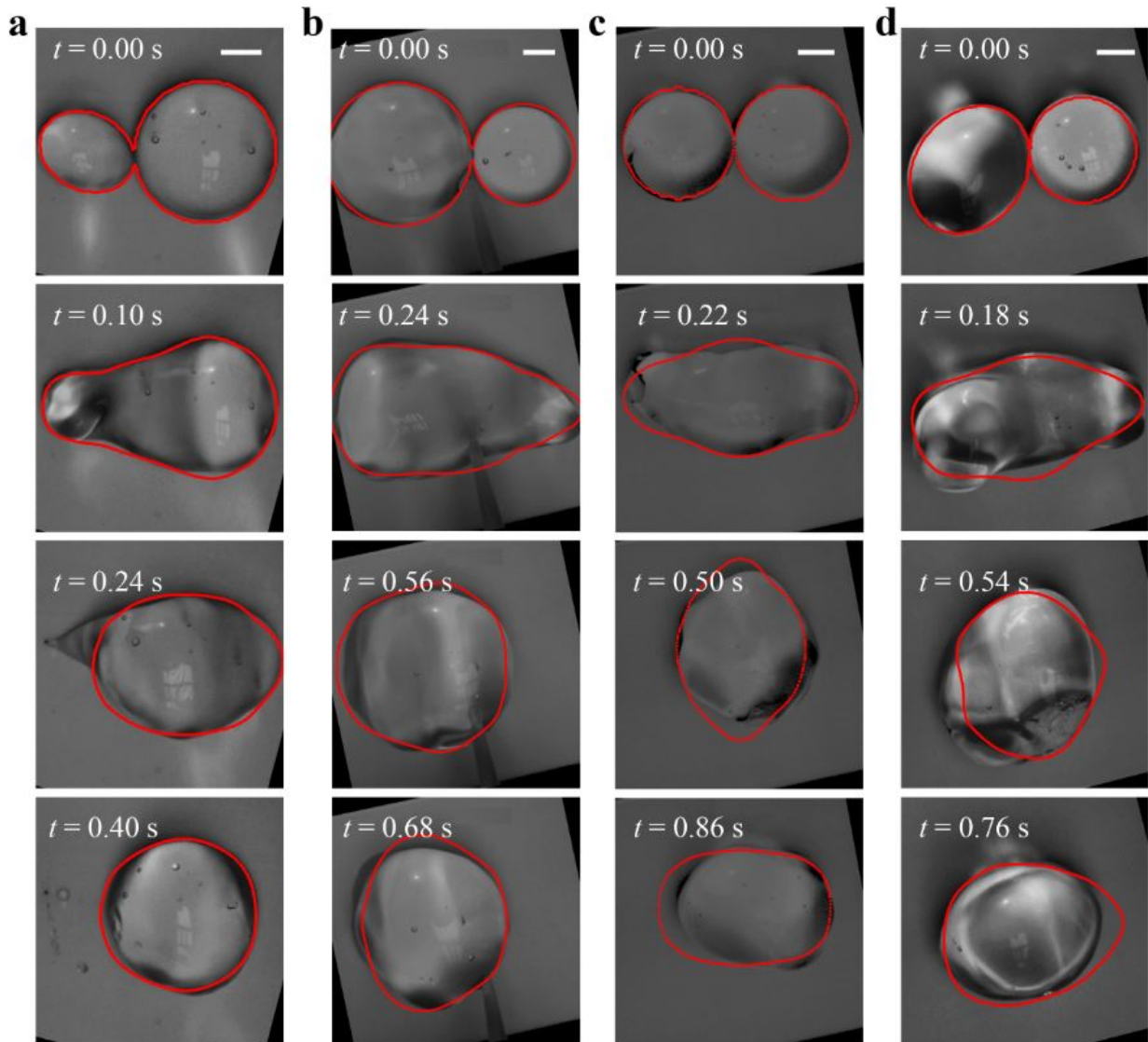


Figure 7. Images of the experimental time evolution of drop coalescence overlaid with simulated predictions (red lines). The scale bars are 1 cm. This figure is reproduced from McCraney et al. (2022a). Reprinted from *Physics of Fluids*, 34, J. McCraney, J. Ludwicki, J. Bostwick, S. Daniel, and P. Steen, Coalescence-induced droplet spreading: Experiments aboard the International Space Station, 122110, Copyright (2022), with the permission of AIP Publishing

oscillations to periodically force the contact line motion of a substrate-attached drop. The second setup used an electro-wetting-based trigger to induce a transient droplet-droplet coalescence event with large sweeping by contact lines. The droplet mobility was measured for both experiments for use in predictions of inertial spreading.

Using the first experimental setup, McCraney et al. (2022b) analyzed the shape oscillations of sessile water droplets with full mobility contact lines in microgravity for applications in industrial processes such as spray cooling, lithography, and the assembly of autonomous fluidic machines. Water was

the fluid, and nine substrates with a wide range of wetting properties were prepared. A 10 ml centimeter-scale water drop was placed on a partially wetting substrate using a syringe, and the mechanical wave driver was used to induce oscillations. All the experiments produced drop resonances with a harmonic response, which is in contrast to Earth-based experiments of pinned drops. Figure 6 shows frequency as a function of static contact angle with microgravity experimental measurements and theoretical predictions. The results indicate that the experiments did produce drops with freely moving contact lines and that their model captures

the essential physics of oscillating sessile drops with freely moving contact lines.

Using the second experimental setup, McCraney et al. (2022a) observed coalescence-induced droplet spreading in microgravity (McCraney et al., 2022a). Four hydrophobic substrates made of Teflon were prepared and sanded to various surface finishes. For each experiment, a pre-positioned liquid drop was deposited on the surface using a syringe, and a second drop was grown near the first drop until coalescence began to occur, as shown in the top row of Figure 7, which shows the time evolution of drop coalescence for several surfaces. Using the acquired data, McCraney et al. (2022a) were able to determine that the contact line mobility M is a material parameter by experimentally measuring M for a given solid-liquid-gas configuration via plane normal surface vibrations of a sessile drop and then using that value of M to model another flow of interest with the Davis–Hocking model without fit parameters. This experiment elucidates an improved understanding of inertial-capillary spreading for a pair of coalescing wall-bound drops and validates widely accepted theoretical predictions. The results may have relevance for rainwater runoff, cell-cell interaction, steam condensation, thermal management, and electrowetting (McCraney et al., 2022a).

Current and Ongoing Research

In addition to the significant advances in transport phenomena research enabled by microgravity illustrated above, there are many recent and ongoing research investigations sponsored by the ISS National Lab via the NSF-CASIS collaboration that promise fruitful results.

Combustion

Using solid fuels and the Solid Fuel Ignition and Extinction (SoFIE) chamber insert in the CIR, a group of researchers is studying a steady flame's response to a non-steady forced airflow. A better understanding of periodic or intermittent flame spread using solid fuels will lead to improved models and a better understanding of intermittent flame processes in applications such as wildland fire spread, which is a significant contributor to pollution and a threat to communities.

5.2 Heat Transfer and Multiphase Flow

At the time of this work, there are five ISS National Lab sponsored investigations using NASA's Flow Boiling and Condensation Experiment (FBCE) hardware. The first investigation is using the Flow Boiling Module (FBM) to obtain CHF and flow boiling data to create deep models of flow boiling using machine learning techniques. The deep models will be used to predict flow patterns, heat transfer rate, and CHF under varying gravity conditions. The second

investigation is using the FBM and the Condensation Module for Heat Transfer (CM-HT) and applying periodic perturbations of the operating parameters to force transients and instabilities in flow boiling and condensation, which will improve our understanding of multiphase flow heat transfer in microgravity. The third investigation is using the CM-HT to systematically characterize two types of transient behaviors of flow condensation to examine their impacts on the condensation rate and explore working conditions that can generate two-phase oscillation to enhance flow condensation in a smooth tube. Their work has the potential to improve our understanding of flow condensation on Earth, leading to more efficient and smaller condensers. The fourth investigation will use the CM-HT on the ISS to capture the effects of turbulence and interfacial waviness on the heat transfer characteristics of a condensing film. This will enable the development of more accurate design tools for condenser systems on Earth. The final investigation will use the CM-HT, coupled with acoustic emission sensing, to probe the physical mechanisms that dominate flow instabilities in condensation. The acquired data will allow the team to quantify the roles of turbulent diffusion, liquid film, and interfacial waves during the transition from stable annular flow condensation to metastable wavy annular flow, churn flow, and the slug flow regimes. These quantifications will provide valuable insights into the design and optimization of condensers on Earth.

Another investigation is using a commercial facility to extend the study of heat pipes in microgravity. The first goal of the study is focused on investigating 50:50 mixtures of pentane and isohexane. The second goal is to understand the fundamental flow and stability questions of pure fluids in heat pipes in microgravity. The third goal is to model the performance of the heat pipe in microgravity and elucidate the details of the heat transfer behavior and meniscus flow. The results of this work will address several fundamental questions in multiphase heat and mass transfer for applications in energy conversion, distillation, microelectronics, self-assembly coating processes, and space exploration.

Two investigations are using a commercial multipurpose platform to conduct their ISS investigations. One investigation is using light-tuning surfactants to de-pin bubbles and droplets on demand (i.e., the photo-Marangoni effect) to manipulate multiphase fluid motion. The results of this investigation could prove beneficial for controlling and enhancing boiling heat transfer for Earth-based applications such as power generation, thermal management, and desalination. The second investigation is studying the transition between long-wave and short-wave instabilities in thin films undergoing evaporation for potential applications in cooling and manufacturing.

Another investigation using a commercial multipurpose platform is investigating shrinking surface bubble deposition (SSBD) in microgravity to understand the fundamental

mechanisms of suspended nanoparticle deposition due to multi-scale plasmonic bubble behavior and the surround flow phenomena. The results of this work will inform the development of Earth-based fabrication methods for highly sensitive biosensors.

Fluid Dynamics

There are two recent or ongoing investigations focused on fluid dynamics. The first investigation is studying the dynamics of liquid-liquid phase separation (LLPS) using a microtubule-based active fluid. The investigation will elucidate unique properties of active-LLPS that are strongly affected by gravity and establish unique methods of controlling interfacial structure and fluctuations. The results of this work will be important for improving the fundamental understanding of LLPS in cell biology. Furthermore, active-LLPS may be used to create the next generation of soft active materials for more lifelike robots.

The second investigation seeks to investigate the effect of gravity on the threshold and nature of the Faraday instability. The investigation will experimentally verify a model for the Faraday instability in microgravity and compare the model with ground results and theory. The results of the investigation may be important for applications such as jetting processes, interfacial tension measurements for predictive additive manufacturing, and microscale heat transfer.

Complex Fluids and Particulate Flows

Several ongoing investigations are studying fundamental transport phenomena using complex fluids. One investigation is using microgravity to study dry foams and emulsions, specifically, their stability, breakdown, and phase separation. The results of this work will provide an improved fundamental understanding of foams and emulsions to inform improvements of the foams and emulsions used in everyday life (e.g., foam cups, fire extinguishers, ice cream, salad dressing, and shaving cream).

Another investigation is using microgravity to create well-defined transport conditions to study particle adsorption to a droplet interface. Particle-laden fluid interfaces have important applications in sensing, catalysis, optical materials, and environmental remediation. The results of this work will inform modifications to Earth-based systems.

A third project seeks to improve aggregation models by exploring and quantifying the dynamics of particles at an interface and in a bulk fluid in microgravity. Particle-laden fluids and particles in fluid-gas interfaces on Earth are of critical importance and have a wide range of applications, including pollen deposition, storm-transported sea salt in bodies of water, algae growth, and fluidized granular materials.

A fourth investigation is studying the physics of colloidal gelation, coarsening, and phase separation in bimodal

attractive colloidal suspensions in which the size difference between the two different particle types is significant. The persistent microgravity environment will enable the team to advance predictive computational models and advance the fundamental understanding of colloidal gels for Earth applications in which large particle size difference is unavoidable, such as hydrogels, advanced carriers for drug delivery, and cement analogs.

A fifth ongoing project seeks to provide a comprehensive understanding of the complex physical mechanisms that control the mobility of individual active colloids and their collective behavior to optimize active colloid transport. The results will also elucidate the impact of microgravity on collective dynamics and non-equilibrium interactions of active matter. The successful completion of this investigation will yield important results for applications in microfluidics, nanofluidics, medical devices, pharmaceuticals, and several other research areas.

A sixth ongoing investigation seeks to measure the thermophoretic motion of particles in complex fluids in microgravity to aid in the design of next-generation microfluidic bioseparation devices for label-free viral load detection. The team is utilizing multiple particle-tracking microrheology to obtain local thermophoretic and rheological data.

The final complex fluids investigation aims to observe and quantify the thermophoresis of colloidal microparticles in air in microgravity. Several particle materials, sizes, and shapes will be investigated. Particle velocity will be quantified using particle tracking velocimetry. The results of this work are expected to advance the field of active matter by providing the first demonstration of colloidal thermophoresis in three dimensions in a gaseous environment.

Biophysics

Several recent and ongoing investigations are studying biophysics in microgravity. One ongoing investigation is using unique side-emitting optical fibers (SEOFs) attached to light-emitting diodes that create germicidal light to study how the use of light scattering and photocatalysis influences the ability of ultraviolet (UV) light to prevent biofilm formation in microgravity. Bacterial growth and biofilm formation processes can differ in microgravity relative to Earth, and little is known about the sensitivity of biofilms to germicidal UV in microgravity. The results of this work will have important implications for the use of germicidal UV to prevent biofilm formation in microgravity and for improving our understanding of the effects of gravity on biofilm formation for Earth-based applications.

Three investigations are using the NASA-owned Ring Sheared Drop (RSD) hardware. The first investigation is developing and testing predictive models of non-Newtonian flow of high-concentration proteins at an interface. The results will

improve the understanding of, and ability to control, protein aggregation in systems with a large protein concentration near free surfaces, which is important for applications in pharmaceutical manufacturing and drug development. The second investigation will use the RSD hardware with multiple protein types to improve the fundamental understanding of protein association, aggregation, and gelation in systems with a high protein concentration near free surfaces. The results of this work will enable the development of predictive models for industry applications, such as the manufacturing of pharmaceuticals. The final investigation using the RSD hardware will study pellicle formation at a drop interface. The team will investigate the transport of bacteria to, and oxygen from, an interface, and pellicle morphogenesis at a spherical interface. This would be the first observation of pellicle morphogenesis at a spherical interface, and the results would improve the fundamental understanding of soft tissue morphogenesis.

Another biophysics investigation will use a commercial multipurpose facility to study the impact of gravity and interfacial forces on the development of biofilms in porous media. The experiments and measurement techniques will enable the creation of a phase diagram that relates dimensionless parameters to different biofilm growth and architectures. The data generated will elucidate the mechanisms that govern biofilm growth and structural evolution in porous media on Earth.

Materials Science

There are three recent or ongoing investigations studying materials science in microgravity. The first investigation is synthesizing graphene-based hydrogels in microgravity, and then transforming them into graphene aerogels. The investigation seeks to study the growth behavior of the graphene hydrogels in microgravity and to examine and explain the influence of microgravity synthesis on the 3D mesostructured and multi-physical properties of the resulting graphene aerogels. An improved fundamental understanding of crosslinking and drying will enable the synthesis of graphene aerogels with improved thermal, electrical, and mechanical properties for Earth-based applications in nanoelectronics, energy storage, and composites.

The second materials science investigation seeks to grow metal-organic framework (MOF) crystals in microgravity. Microgravity will elucidate the fundamental mechanisms of growth, morphology, and defect generation of MOF crystals, which ultimately determines the resulting properties. MOFs have several Earth-based applications, such as hydrogen storage, membrane separation, water splitting, and nanoelectronics, due to their tunable chemical, electrical, and mechanical properties.

The final materials science project is using the phase and composition evolution of Ti_3C_2 -silicon oxycarbide (SiOC) and TiC-SiC high-temperature composites with both dense and porous structures to understand atomic- and nano-level species interactions under different gravity conditions (i.e., Earth and microgravity). These high-temperature composites represent a new class of high-temperature stable and electrically conductive materials. The results of this work will provide a fundamental understanding of achieving high-temperature, conductive, dense or porous, and nanostructured composites. The findings will also enable a fundamental understanding of the new SiOC system, providing new science and directions in materials synthesis to benefit life on Earth.

The Future of Transport Phenomena Research in Microgravity

The above studies only scratch the surface of the potential scientific impacts that transport phenomena research in persistent microgravity can have for life on Earth. As illustrated by the investigations outlined in this work, removing gravity allows researchers to study phenomena not attainable on Earth, enabling groundbreaking scientific results for humanity. At the time of this work, the ISS is slated to be decommissioned in 2030. However, the future of microgravity research is promising. As NASA and the rest of the space community work to build a sustainable LEO economy (Mazzucato and Robinson, 2018), several microgravity research platforms with new and exciting scientific capabilities are being planned (Zea et al., 2024).

Conclusions

The NSF-CASIS collaboration has facilitated numerous investigations onboard the ISS, enabling fundamental discoveries in multiple facets of transport phenomena. This has led to an expanded understanding in several research areas. The knowledge gained promises to translate into design advancements, improved process control, and will contribute to use-inspired advances in food, energy, pollution control, nanotechnology, and health care.

The ISS has enabled a human presence and novel research in space for more than two decades. It is imperative that the ISS research capabilities be fully utilized through mutually beneficial fruitful collaborations to benefit life on Earth while the ISS is still available. Until the ISS is decommissioned, the ISS National Lab is committed to facilitating ground-breaking research onboard the orbiting laboratory through productive collaborations such as that of the NSF and CASIS.

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