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2019 NASA Division of Space Life and Physical Sciences Research and Applications Fluid Physics Workshop Report

Final Report

August 2020

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Preface

Workshop Presentations

Presentations from the 2019 NASA SLPSRA Fluid Physics Workshop are available at the website: http://www.cvent.com/events/2019-nasa-slpsra-fluid-physics-workshop/custom-17-0a98f56ee636488d9bc4675674d50337.aspx.

About the Sponsoring Organizations

NASA SLPSRA: The Division of Space Life and Physical Sciences Research and Applications (SLPSRA) was established as part of NASA's Human Exploration and Operations Mission Directorate in 2011. SLPSRA administers NASA's Life and Physical Sciences Research, which includes the Human Research, Space Biology, and Physical Sciences Programs, to enable human spaceflight exploration and pioneer scientific discovery in and beyond low Earth orbit. To learn more about SLPSRA, visit www.nasa.gov/content/slpsra-overview.

Executive Summary

On October 16 and 17, 2019, NASA's Space Life and Physical Sciences Research and Applications (SLPSRA) Division held the 2019 NASA SLPSRA Fluid Physics Workshop at the Glenn Research Center in Cleveland, Ohio. Researchers from academia, industry, and Government agencies gathered to provide recommendations to NASA on exploration-related microgravity challenges in multiphase systems and thermal transport processes.

The goal of the workshop was to identify overarching future research themes relevant to NASA's exploration goals in three key areas: (1) boiling and condensation; (2) water recovery; and (3) heat pipes.

In the boiling and condensation topic area. Proposed research should focus on the following:

1. Developing methods and technologies for increasing the critical heat flux (CHF) and heat transfer coefficient that facilitate bubble removal during boiling.
2. Exploring onset of bubble nucleation, bubble coalescence, convective boiling heat transfer, and void fraction distribution up to CHF and developing mechanisms based on improved understanding of these features in flow and pool boiling under a range of gravitational forces.
3. Examining instabilities in two-phase flows and developing strategies to take advantage of or avoid instabilities such as density wave oscillations, Ledinegg instability, flow maldistribution and pressure drop oscillation, startup transients, loss of coolant effects, and effects of noncondensable gases.
4. Focus on strategies that will enhance flow and dropwise condensation and separation of noncondensables in reduced gravity as well as focus on surface wettability and two-phase manipulation on condensation surfaces.
5. Developing applied research that aims at understanding performance and instabilities of vapor-compression refrigeration systems in microgravity and partial-gravity environments.

In the topic area of water recovery, suggested and recommended research focuses:

1. Developing research toward improved understanding of multiphase adiabatic and nonadiabatic fluid physics including phase separation, dispersed phase breakup, entrainment, and coalescence, multiphase flows and reacting systems, evaporation and condensation, and fluid management.
2. Developing research that focuses on the fundamental improvement of current technologies (rotary separators, passive membrane separators, catalytic reactor, and urine distillation) that are being used on the International Space Station (ISS) using the additional and improved understanding of the multiphase flow physics.
3. Developing research programs that address advanced diagnostic techniques with full-field measurements that are needed to verify phase change and that address rheology of suspensions in inertial regimes, water purification, bubble coalescence and removal in packed bed, and surface modification for condensation enhancement.

In the topic area of heat pipes, fundamental science in heat pipes and heat pipe devices were identified as areas of research:

1. Interfacial and intermolecular phenomena: Focus research at a more comprehensive understanding of surface modification effects, working fluids and phase-change kinetics, fluid mixture physics, high- and low-temperature systems, wicking versus wickless designs, resonant enhancement, material properties, fabrication methods and processes, heat integration, and process intensification.

2. Modeling, simulation, and performance prediction: Improve the two-phase continuum models, couple models of phase change with bulk fluid flow and heat transfer, blend continuum and molecular simulation, and develop machine learning and artificial intelligence algorithms to predict the behavior of complex systems like oscillating heat pipes (OHPs).

In the heat pipe device and system area, four themes for research were identified:

1. Variable thermal links for lunar and Martian landers, rovers, and human habitats
2. Freeze and thaw of long pipes with grooved condensers
3. Long and three-dimensional (3D) pulsating heat pipes
4. Standardization of performance metrics and testing procedures

Moreover, the heat pipe panel made programmatic recommendations that included

1. Developing a multiuser, modular, heat pipe facility aboard the ISS that can handle fundamental thermal-fluid experiments and evaluate prototype heat pipe device designs.
2. Establishing a working group to define a set of standard performance measures for heat pipes, akin to an American Society for Testing and Materials (ASTM) International standard set, so different designs and configurations can be compared with one another.
3. Developing a plan for handling proprietary information and intellectual property that may result from work done on the ISS National Laboratory.
4. Identifying opportunities for inter-agency and international research collaborations and funding. Of particular interest are Air Force Office of Scientific Research (AFOSR), Office of Naval Research (ONR), Defense Advanced Research Projects Agency (DARPA), and National Science Foundation (NSF).

Contents

1.0 Workshop Overview and Objectives

On October 16 and 17, 2019, NASA's Space Life and Physical Sciences Research and Applications (SLPSRA) Division held the 2019 NASA SLPSRA Fluid Physics Workshop at the NASA Glenn Research Center at Lewis Field. This workshop brought together Government, university, and industry engineers interested in the technology challenges caused by the reduced-gravity environment on fluid-handling heat-transfer processes in space. A total of 185 individuals registered and attended various sessions of the workshop. The registrants and their affiliation are listed in Appendix B. The full agenda for the workshop is provided in Appendix C.

The workshop was held to help define future research directions for the microgravity fluid physics program, especially as they relate to NASA's exploration goals. NASA's SLPSRA Division is planning research in support of technology development to enable human spaceflight beyond Earth orbit, and investigations into the behavior of fluids that enable NASA's exploration goals are of particular interest.

Enacting Space Policy Directive 1: Reinvigorating America's Human Space Exploration Program (Ref. 1) will require the ability to utilize and control fluids for every aspect of space exploration, from Earth launch to transit to human habitation on the Moon and Mars.

The International Space Station (ISS) provides researchers the ability to conduct long-duration experiments in low Earth orbit, enabling scientists, engineers, and technologists to pursue innovations and discoveries not achievable by other means. Fluid physics encompasses a breadth of research areas made accessible in an environment where gravity-driven phenomena such as buoyancy-driven fluid flows and sedimentation are nearly negligible, allowing scientists to observe and control fluid phenomena in ways that are not possible on Earth. Besides the ISS, there are a variety of other platforms that exploit the reduced-gravity environment for the development and testing of new technologies.

This workshop focused on the identification of future fluid physics investigations that address the goals of NASA. In advance of the workshop, a Request for Information (RFI), NASA Research Announcement NNH19ZTT003L, was issued by NASA requesting input for the workshop. The RFI responses were used to stimulate the discussions during the breakout sessions. See Appendix D for the listing and categorization of the RFI responses received.

The first portion of the workshop, a plenary session, consisted of invited presentations regarding the current technologies and future development plans for the NASA low-gravity physics program. Also included were the state of understanding regarding relevant fundamental fluid behavior and currently available experimental hardware for use on the ISS. The latter portion of the workshop consisted of three parallel breakout sessions focused on ideas or topic areas presented in the earlier briefings, as well as in responses to the RFI issued in advance of the workshop. Each breakout session was led by a Chair and Co-Chair and accompanied by a session facilitator. The Chairs selected represented expertise in the applied research in the topic area, while the Co-Chairs were experts from a university. The facilitator was a topic area expert from NASA Glenn Research Center. The purpose of the breakout sessions was to promote discussion on current gaps in the understanding of relevant low-gravity issues, which, if resolved, would lead to improved system performance or contribute to a better understanding of fluid phenomena in space systems. The three breakout session topics were

- Boiling and condensation: specifically the application of phase change as it applies to space power, cryogenic propellants, and thermal control.
- Water recovery: collecting wastewater from crew urine, cabin humidity condensate, and CO_2 reduction (Sabatier) product water, and subsequently processing it into potable water. Currently,

the overall water recovery rate aboard the ISS exceeds 90 percent of the water, with plans to extend the recovery for exploration missions to virtually 100 percent.

- Heat pipes: includes capillary-based pumped loops, vapor chambers, evaporators, condensing radiators, and oscillating heat pipes.

This report summarizes the breakout session discussions from the workshop. The objectives were to identify potential future investigations that address NASA's exploration needs and to recommend follow-on actions. The breakout session sections (Sections 2, 3, and 4) of the report were written by the Chairs and Co-Chairs that led each session. The concepts and ideas presented in RFI responses, as well as new ideas presented by the session participants, were consolidated by the Chairs and Co-Chairs into the key recommendations presented in each section and summarized in the Executive Summary.

1.1 References

1. Trump, Donald: Space Policy Directive 1: Reinvigorating America's Human Space Exploration Program. Federal Register, vol. 82, no. 239, 2017, pp. 59501–59502.

2.0 Topic Area Report: Boiling and Condensation

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2.1 Introduction

The boiling and condensation breakout session was one of three sessions held during the NASA SLPSRA sponsored Fluid Physics Workshop held at Glenn on October 16 and 17, 2019. The breakout session was well attended with over 80 participants from academia, industry, and Government. The majority of the session included presentations by authors of concepts submitted through the RFI. The session included boiling and condensation topics relevant to thermal control systems, space and planetary systems, and cryogenic propellant storage and handling. Fifteen responses to the RFI were submitted prior to the workshop. Twelve concepts were presented by the authors in attendance (three authors were unable to attend) and an additional three “walk-on” concepts were presented and discussed. Time was allocated at the end for an open discussion. Based on the presentations and discussions, the breakout session panel developed this summary report.

This report summarizes the discussions by organizing the content into following major themes:

- Boiling (pool and flow)
- Condensation
- Fundamental fluid behavior
- Two-phase system behavior
- Instrumentation, diagnostics, and facilities

Each theme is organized to provide arguments and justification to NASA when prioritizing research funding decisions by including a ranking, objectives, scientific and technical merit, microgravity justification, terrestrial applications, benefits to NASA, significance and impact, research partners, and facilities. In many cases, there is overlap, but the intent was to provide a complete justification for each theme area. The RFI responses and additional concepts presented during the session are listed in Appendix D.

2.2 General Remarks on Relevance to NASA

For the research to be relevant to NASA, it is important to note that the purpose of each breakout session in this workshop was to promote discussion on current gaps in understanding of relevant low-gravity issues, which, if resolved, would lead to improved system performance or contribute to a better understanding of fluid behavior in space systems. The emphasis was placed on concepts that can improve system efficiency and/or reduce system mass for NASA's exploration missions, which include Earth and lunar orbiting platforms (ISS and Lunar Gateway) as well as lunar and Martian surface exploration. For example, it is envisioned that tens of tons of cryogenic hydrogen fuel, needed for lunar sustainability and during Mars transit, will need to be transferred and stored with negligible losses for up to a year at the Lunar Gateway. Initially, warm lines between the cold donor tank and warm receiver tank will be cooled by flow boiling of the propellant, and the vapor produced will be condensed and recycled in return lines to the receiver tank. The receiver tank will also need to be cooled through pool-boiling processes. Understanding of pool and flow boiling, as well as condensation, in microgravity are important for proper design of fill and transfer of the cryogenic propellant. The fuel transfer processes of interest are intrinsically transient and may involve time-varying system pressure (which makes the saturation temperature vary) and time-varying wall temperatures for the boiling and/or condensation processes that occur due to progressive cooling of the receiver tank structures. Exploration of transient effects of these sorts would contribute to better design of systems to accomplish the performance objectives of the fuel transfer processes needed for future missions.

Ultimately, the goal is for NASA and industry to be able to design reliable two-phase systems for use in approximately 0, 1/6, and 3/8 Earth-normal gravity environments. Large systems must be scaled for extended normal gravity testing (or testing in a centrifuge or on aircraft following reduced-gravity flight profiles) so that the two-phase phenomena are similar between ground testing and flight operations. Where this is not possible, reliable predictive models are essential to support the proper designs and operations. Methodologies must be developed to allow scaling between normal, partial, and microgravity that include the relevant dimensionless groups, ranking of these groups in terms of influence for a specific design, and identification of the minimum number of dimensionless groups that must be matched for reasonable scaling.

2.3 Pool and Flow Boiling Issues in Microgravity and Partial-Gravity Environments

Rank: High Priority

2.3.1 Objectives

In general, boiling is a highly effective mode of heat transfer with high heat flux levels driven by relatively small temperature differences between the heated wall and the liquid. The high heat transfer coefficients make these processes attractive for many terrestrial and space applications including compact evaporators in the thermal control of aircraft avionics and spacecraft environments, electronic cooling, and boiloff of cryogenic fuels. In spite of its efficiency, cooling based on liquid-vapor phase-change processes has not yet found wide application in space due to specific process uncertainties and related reliability problems associated with partial-gravity and microgravity environments. Although most future two-phase space systems plan to use flow boiling, pool boiling remains of interest since it is a special case of flow boiling, provides fundamental understanding of boiling physics, and pool boiling models often feed into flow boiling models. A key challenge in developing two-phase thermal systems is the development of a heat transfer database and reliable models for boiling in variable gravity environments from which the performance of two-phase heat exchangers in spacecraft can be predicted with confidence.

The results from the Nucleate Pool Boiling Experiment and Microheater Array Boiling Experiment that comprised the Boiling Experiment Facility (BXF) on the ISS provided much needed clarification regarding fundamentals of bubble growth in microgravity and scaling laws for boiling curves. Additional research, however, is needed in methods to increase critical heat flux (CHF) and dryout and heat transfer coefficient either through surface modification to increase nucleation sites or through patterning surfaces to facilitate bubble removal. Methods to remove bubbles using external forces to partially replace gravity should also be investigated. Existing models used to scale boiling behavior from 1g to partial gravity and microgravity conditions for smooth surfaces will need to be verified and/or new models should be developed.

Flow boiling is a critically important process in power and environmental thermal management systems that use phase change of a working fluid to provide efficient heat transport in important terrestrial and space applications. Flow boiling is especially important in spacecraft and habitat thermal control systems and Rankine-cycle power systems. Flow boiling in an evaporator unit at less than Earth-normal gravity may occur in thermal control systems that incorporate a pumped two-phase loop to transport heat, and will occur in refrigeration or heat pump systems. Flow boiling may also result during transfer of cryogenic liquids if flow conduits and/or storage vessel walls have hot spots, or if a transient drop in pressure lowers the saturation temperature of the fluid. The role that flow boiling plays in these applications makes accurate prediction of flow boiling performance critically important in thermal control, cryogenic fluid management, and power systems for next-generation NASA systems for manned missions to the Moon and Mars. In addition, these longer duration manned missions require systems that must function for longer times compared to earlier missions, and understanding how progressive small changes in system operating conditions may affect flow boiling mechanisms under reduced gravity will take on increased importance.

Mechanisms of flow boiling overlap with those of pool boiling, so research on variable gravity effects in one may yield better fundamental understanding and modeling capabilities that apply to both. In particular, mechanisms for the onset of nucleation, bubble ebullition, and CHF may be similar for pool boiling and flow boiling for low-inertia flows and the impact of reduced gravity on these mechanisms may be similar. The mechanisms in these circumstances share a connection to transport of boiling-generated vapor away from the passage walls, which is often facilitated by buoyancy forces under 1g conditions. Under reduced gravity and for low-inertia flows, the flow boiling system will likely have similar to slightly higher capability to move vapor away from the channel wall when compared to pool boiling, which can promote a CHF transition and the associated dramatic drop in heat transfer performance. Recent research suggests ways to manipulate flow boiling mechanisms that can act to enhance flow boiling heat transfer under microgravity conditions.

To facilitate design of systems that incorporate flow boiling for reduced-gravity conditions, a thorough understanding of variable gravity effects on flow boiling is needed, together with the capability to model the effects and predict the performance of the system under the design conditions of interest. Research in this area should emphasize obtaining highly resolved temperature, flow, and void fraction field data for flow boiling processes, and include explorations of CHF and dryout, approaches to delay CHF and dryout, onset of nucleate boiling, bubble growth and release, and development and validation of fundamental phenomenological models. Innovative approaches to instrumentation and data acquisition (DAQ) can enhance capabilities to get such detailed data. This could include extensive use of closely spaced, high-frequency response microsensors, and/or tomography (e.g., electrical capacitance type).

Improved capability to synchronize and coordinate flow and process imaging with data collection from sensors would enhance the value of experimental results.

A key challenge in developing two-phase thermal systems is the development of a heat transfer database and reliable models for flow boiling in variable gravity environments from which the performance of two-phase heat exchangers in spacecraft can be predicted with confidence. The development of the database and models should be scoped to benefit development of technologies for space missions as well as to contribute to efforts to develop next-generation terrestrial application systems that are more efficient and have reduced environmental impact.

Research into reduced-gravity effects on CHF mechanisms in flow boiling is arguably of highest priority because failure to accurately design systems to avoid CHF can lead to a catastrophic failure event. This is especially important given that future NASA systems are envisioned that can operate reliably for long-duration missions. A second high-priority topic is two-phase flow instabilities in flow boiling processes, again because instabilities can lead to an excursion to operating conditions that dramatically deteriorate heat transfer. Instabilities on the local boiling level, component level, and in two-phase loops can occur and operation limits and design practices must be established for both ground and microgravity environments. Some instabilities are highly gravity dependent and therefore can be initially investigated in normal gravity with various orientations and then validated in microgravity.

Terrestrial experiments have shown that there are a number of ways of enhancing boiling mechanisms that could mitigate the negative effects of reduced gravity in flow boiling systems. This may include active and passive ways of altering and controlling two-phase flow surface morphology, nucleation, instability, removal of vapor bubbles from surface using, for example, flow inertia, photosensitive surfactants, electric fields, near-surface membranes, angled ridges, nanostructures, etc. Research into the effects of these enhancement techniques on flow boiling at reduced gravity is a third high-priority topic. Experiments exploring convective boiling at heated microstructured and nanostructured surfaces will clarify the physics of boiling at such surfaces by allowing comparison of the boiling processes with and without gravity. Research in this area also has a high probability of leading to development of surfaces that can enhance and/or better control flow boiling processes in systems that operate in reduced gravity.

Scaled-down system testing could be a useful strategy for evaluating spacecraft flow boiling system design. However, to use this approach, it is necessary to determine the dimensionless groups that must be matched for accurate experimental modeling of flow boiling systems. To develop this capability, research studies are needed to demonstrate which dimensionless parameters (Martinelli parameter, Froude number Fr, Weber number We, Bond number Bo, Jakob number Ja, etc.) must be matched to ensure the scaled-down system accurately models a full-scale system for mission applications.

Flow boiling in bubbly, slug, and annular regimes is common in evaporators or boilers for thermal control, refrigeration, and Rankine power systems, so performance in these regimes is centrally important. In addition, film boiling and transitional boiling through the Leidenfrost point to CHF can occur during filling of cryogenic tanks and propellant transfer lines as they cool. These regimes can also occur during fuel and oxidizer cooling of rocket nozzles, transition to mist flow in evaporators, and quenching of metals and nuclear fuel rods. Gravity can affect the thickness of the vapor layer and affect the stability of liquid-vapor interfaces. Although some quenching experiments in microgravity have been performed, very little data is available regarding reduced gravity on rewetting temperature and heat transfer during transition and film boiling.

Numerical simulations can provide insight into flow boiling physics at scales that are not possible with experimental techniques and can be a cost-effective way to design new systems. Simulations that faithfully resolve all of the relevant scales are currently too complex, however, so continued development of accurate subgrid models and efficient numerical methods to simulate large systems involving phase change are required. Experiments and simulations should be tightly coupled so experiments provide the needed boundary and initial conditions required for simulations, and simulations should provide insight into experimental results.

2.3.2 Scientific and Technical Merit

Gravitational acceleration is a key parameter in flow boiling processes because the large difference between liquid and vapor density in such processes often has a strong impact on the flow morphology of the two-phase system. Conducting longer-duration flow boiling experiments at reduced gravity is a tremendously valuable way to explore the mechanisms of these processes. Previous experimental studies clearly indicate that the heat transfer rate is strongly impacted by the flow morphology. Comparing results of experiments at various reduced-gravity levels with those at 1g can lead to better understanding of how gravity affects the mechanisms of flow boiling processes in general, leading to the ability to model and predict flow and transport in boiling processes in space applications.

The use of advanced instrumentation and DAQ systems to obtain full-field data for pool and flow boiling processes, and improved modeling that will be developed from such data will have a game-changing impact on this field. This research will provide a valuable database for model development and will significantly improve the understanding of boiling physics. There are no obvious technical barriers to obtaining this type of full-field data. Recently developed instrumentation techniques and high-speed DAQ provide an unprecedented opportunity to obtain high-quality data that are highly resolved spatially and temporally. There is a clear pathway to the design of boiling experiments for the Fluid Integrated Rack (FIR) or the Flow Boiling and Condensation Experiment (FBCE) that will provide full-field data that can incorporate an interdisciplinary approach that addresses multiple research questions in a single investigation. An example would be a spectrum of flow boiling experiments with different fluids, pressures, orientations, and flow rates (relevant to applications) that obtain data that can be analyzed by multiple investigators to explore onset of bubble nucleation, bubble coalescence, convective boiling heat transfer, and void fraction distribution up to departure from nucleate boiling. Conditions where flow boiling components or two-phase system instabilities occur can be predicted with models validated by terrestrial, Martian, lunar, and microgravity experiments. Fundamental aspects of these experiments will greatly enhance the body of scientific knowledge regarding boiling, and the improved modeling that results from them will aid in the design of microgravity engineering systems utilizing phase-change fluids that range from liquid metal to cryogenic fluids.

2.3.3 Microgravity Justification

Gravity can change the morphology of the two-phase flow during flow boiling by preferentially skewing the liquid phase distribution in the direction of the gravity body force acting on the fluid. The flow morphology of the two-phase system profoundly affects the primary mechanisms of the boiling process. Consequently, liquid replenishment and vapor removal from the heating surface, the resulting heat transfer, transients leading to CHF, and two-phase flow instabilities are strongly affected by gravity. Full-field data for long-duration boiling in stable microgravity does not yet exist, and is essential to validate accurate modeling of boiling processes and design of devices and systems in which boiling occurs. Long-duration boiling experiments are vital to development of more complete understanding of boiling physics, and steady-flow, long-duration testing of flow boiling in new evaporator design concepts at operating conditions anticipated for applications is the best way to verify their performance and assess their reliability.

As discussed previously, the ability of photosensitive surfactants, electric fields, near-surface membranes, angled ridges, nanostructures, and other active and passive ways to mitigate the negative impact of reduced gravity in pool boiling can only be demonstrated if these strategies are tested in reduced- or low-gravity environments. Furthermore, to facilitate confident scale-model testing of flow boiling systems for spacecraft, reduced-gravity flow boiling studies are needed to demonstrate which dimensionless parameters (Martinelli parameter, Fr, We, Bo, Ja, etc.) must be matched to ensure that a scaled-down system accurately models a full-scale system for mission applications.

2.3.4 Terrestrial Applications

Boiling processes are critically important to a wide variety of terrestrial applications including large steam Rankine-cycle electric power plants, high-heat flux electronics cooling, refrigeration in food processing, storage, and transportation, chemical and medical processing, building heating and air conditioning, and automotive air conditioning. Improved understanding of flow boiling physics and the modeling capability that will result from this research will facilitate the design of boilers for electric power generation that will enhance performance and reduce cost and environmental impact. It has the potential to improve evaporators and boilers for both liquid metal and organic Rankine-cycle systems used for waste heat rejection and primary power generation. The electric power, building air conditioning and electronics cooling industries are all multibillion-dollar-per-year industries in the U.S. alone. Boiling of a coolant is an increasingly attractive potential strategy for thermal management of electronics with progressively increasing power density. The flow boiling research recommended here has the potential to open up new technology pathways that can lead to development of groundbreaking next-generation systems in these industries.

The vapor-compression cooling systems used for most building air-conditioning applications and process refrigeration use flow boiling of the refrigerant to extract heat and moisture from air in warm summer months. The energy efficiency of this widely used system will directly benefit from technologies developed from this research that enhance the effectiveness of flow boiling processes. Vapor compression cycles are also used in many process industries, which include food, drugs, chemical, and medical applications. Likewise, these applications can certainly benefit from advancements in boiling technology. Development of new refrigerants for such systems that are not greenhouse gases is an important challenge for the next decade. Microgravity flow boiling research will contribute to the development of next-generation refrigerants that transfer heat more efficiently in the boiling process and minimize environmental effects.

Flow boiling is also recognized as an efficient means of removing heat from compact electronic devices and boxes with high component densities and thereby high heat fluxes. Improved strategies for implementing compact evaporator coolers for electronic components may facilitate quantum step advances in the compactness and power of microprocessors and other electronic devices. The microgravity boiling research will be particularly valuable to development of micro and mini evaporator cooling for high-power electronics that are insensitive to changes in the g-force environment. This may provide a game-changing technology for cooling avionics subject to variable g-forces due to aircraft or ground vehicle motion.

The broad impact of this research on the important industries discussed in this section is indicative of its very high potential return on investment, and high potential to spark economic growth in these industries.

2.3.5 Benefits to NASA

Boiling processes are critically important to efficient and safe operation of spacecraft thermal management including life support systems for human habitats, and avionics cooling that use two-phase pumped or capillary loops to take advantage of their lightweight and high-performance capabilities. It is also a vitally important mechanism in Rankine power systems and high-power-density energy conversion equipment for long-duration space missions. The improved knowledge of the physics and improved modeling of boiling resulting from this research will facilitate the design of high-performance, high-reliability evaporator and boilers for spacecraft applications, and will significantly reduce the uncertainty associated with using systems employing boiling in space exploration. These systems in which boiling processes play a critically important role are central to the success of future human and robotic exploration. Reduced-gravity flow boiling research can provide benefits to NASA in two specific ways. One is development of advanced, next-generation flow boiling systems that incorporate successful enhancement strategies that emerge from research on use of photosensitive surfactants, ultrasonics, electric fields, near-surface membranes, angled ridges, nanostructures, or other enhancement strategies to mitigate the effects of reduced gravity on flow boiling. A second benefit is that the research clarifies the critical dimensionless groups that have to be matched for equivalent flow boiling conditions would provide the basis to test reduced-scale flow boiling system designs in normal gravity to confirm, with confidence, that they meet performance design specs for future NASA missions. These benefits can enhance NASA’s capabilities to meet system design needs for technologies to support commercial utilization of the Earth and Moon space domain following the Artemis Moon Missions, technologies for human habitats on the Moon and/or Mars, and transport technologies for human missions to Mars.

2.3.6 Significance and Impact

The more highly resolved, full-field data obtained in this research will raise understanding of key flow boiling mechanisms by a quantum step above the current knowledge base. The resulting improved understanding of the physics will facilitate development of more accurate models and enable design of more efficient systems with higher reliability and safety. The use of extensive advanced instrumentation and digital DAQ represents an innovative experimental approach that will also foster the development of advanced tools and techniques to design, and later monitor and control convective boiling processes in terrestrial systems and systems for space applications. Specifically, this may lead, for example, to smart sensor and control systems that can detect precursors to the onset of CHF in flow boiling processes, and prevent a thermal management or power system from reaching conditions that could result in system failure. A system of this type would be a game-changing technology that provides a quantum improvement in the reliability and safety of mission critical thermal management and power systems that use flow boiling processes.

This research will serve multiple applications communities: electric power generation, electronics cooling, building air conditioning, process refrigeration, automotive air conditioning, and green technologies such as solar thermal power and waste heat power generation. The boiling research recommended here has the potential to open up new technology pathways that can lead to development of innovative next-generation systems in these industries. It has strong potential to contribute to the development of evaporator technologies that substantially enhance system efficiency and reliability in these applications, and it can contribute to efforts to develop next-generation refrigerant working fluids that mitigate global warming effects. This research may also enhance boiler operation in fossil fuel and solar thermal power generation, and facilitate development of compact evaporator coolers for electronic components that provide quantum step advances in the compactness and power of microprocessors and other electronic devices. The proposed research is likely to generate projects to develop new evaporator and boiling technologies and/or new smart control systems based on research-generated strategies for enhancing flow boiling processes in the applications areas previously described. Knowledge provided by this research will support robotic scientific exploration of space, and it will provide engineering science knowledge that provides the foundations for next-generation engineering systems that facilitate human explorations missions in space, and commercialization of space.

2.3.7 Research Partners

Because of the wide use of systems in which flow boiling may play an important role, there is a broad spectrum of potential research partners for microgravity boiling research. These may include electrical power producers (such as Pacific Gas and Electric Company (PG&E), Duke Energy Corp., large utilities like Commonwealth Edison Co., etc.), the Electric Power Research Institute, companies in the building and automotive air-conditioning industries (Trane, Carrier, United Technologies Corp., General Motors (GM), etc.), electronics and avionics companies (Intel Corp., Google, Hewlett Packard Enterprise, Honeywell International Inc., Raytheon Technologies Corp., etc.), and Government-funded research agencies connected to energy technologies and spacecraft thermal control (Department of Energy (DOE), NRE, National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory, NASA Glenn Research Center). International collaborations with scientists in Europe, Japan, and China are also possible.

2.3.8 Facilities (New or Existing)

Facilities most likely to be used for microgravity flow boiling research experiments are FIR, BXF, FBCE (with or without modifications), Zero Boil-Off Tank Experiment (ZBOT) for low heat flux, and the Microgravity Science Glovebox (MSG) facility.

Once the planned runs for FBCE are completed, the test matrix for the FBCE may be expanded to cover expected conditions in the supply and return lines using a cryogenic simulant. Once these tests are completed, it is recommended that the flow boiling test section be replaced with a geometry that more closely resembles the actual tank transfer processes. Complementary tests could also be done by replacing the FBCE condensation module for the return line. Additional tests could be conducted for pool boiling, but may require an apparatus different than the FBCE. The data and insight gained would serve to validate models of boiling and condensation, and would be a steppingstone to a larger scale demonstration using actual cryogens.

2.3.9 Remarks

The RFI responses included 13 descriptions of recommended research on flow boiling topics.

2.4 Flow Condensation Issues in Microgravity and Partial-Gravity Environments

Rank: Medium Priority

2.4.1 Objectives

Flow condensation is a crucial part of any two-phase loop system. All thermal management, vapor compression cooling, and Rankine-cycle power systems must contain a condenser to reject heat and return liquid to the evaporator and boiler. Ensuring that reliable and efficient operation of the loop or cycle can be sustained requires a high-performance condenser. Additionally, some cycles require effective subcooling of the working fluid in order to prevent unwanted vapor generation in flow lines or pump cavitation. This makes convective condensation a centrally important process in these systems for both terrestrial and space applications. Despite its importance, there are a number of aspects of convective condensation mechanisms that remain poorly understood, and the inability to accurately model them prevents future advances in the field. High-performance, reliable condensers must be accurately modeled on a fundamental level before pursuing physical designs and demonstrations of these systems. Heat transfer coefficients and heat fluxes in condensers used for heat rejection are typically much lower than those of boiling. Limited heat sinks can also contribute to lower heat fluxes. Consequently, the heat rejection elements of heat exchangers are larger and heavier when used for this purpose. In aerospace and low-gravity applications, this weight penalty is very severe, heightening the importance of efficient condensation methods. To improve the field of knowledge for flow condensation, new research on convective condensation should emphasize obtaining more highly resolved, full-field data to provide insight into fundamental processes. Explorations of noncondensable effects, wave effects, inlet superheat and subcooled effects, enhancement techniques, tapered channels, capillary enhancement techniques, channel and container geometry, surface modifications or wettability, and dropwise condensation should be considered. These investigations will produce a database to facilitate development of better models of the mechanisms previously described. In turn, this will make the design of high-performance condensers possible for both terrestrial and low-gravity applications. In particular, the methods of separation and elimination of noncondensables in the absence of gravity are unproven. Therefore, this demands more design, modeling, and experimental validation in long-term space environments considering noncondensables. Additionally, capillary fluidics research can close the gap in fundamental fluid processes that affect condensation phenomena. Several concepts for experiments in low gravity that would build our understanding of surface wettability and two-phase manipulation include: switchable wettability condensers, sloshing modes identification, coalescence-induced droplet jumping, droplet coalescence, gradient surfaces coalescence, low-frequency nonaxisymmetric modes, high-order mode discovery, walking modes, ‘dinging’ droplet experiments, and oblique impacts. Experiments that clarify the effects of gravity forces on the mechanisms of convective condensation processes described previously would have a lower priority. Exploration of strategies that will enhance convective condensation in reduced gravity will have the highest priority. Gravity effects that thin or redistribute the condensate film will not assist condensation in space applications, although terrestrial experiments have a use for this data. Other driving forces such as vapor shear and surface tension must be employed fully. One approach is the use of tapered flow channels for extending the shear flow regime that will be less dependent on gravity. However, developmental work and demonstrations in various orientations on Earth as well as verification in low-gravity environments are required. Surface contouring approaches and porous coatings (e.g., heat pipes) can promote surface tension as a gravity-independent facilitator in condensation mechanics. Also, the use of nanostructured surfaces or pulsatile flow in condensers may enhance convective condensation in systems that operate at reduced gravity. Experimental investigations that explore enhancement strategies of this type have high potential to produce game-changing condenser technologies, and should therefore be essential components of a low-gravity research plan in this area.

2.4.2 Scientific and Technical Merit

In convective condensation, gravitational acceleration strongly affects flow and transport processes. Because of the large density differences between the liquid and vapor phases, gravity tends to preferentially shift the liquid phase along the direction of the gravity vector. The resulting stratification of two-phase flow strongly impacts the heat transfer in the condensation process. Two-phase flow and transport in convective condensation processes are complex, making it challenging to obtain full-field data that provides a complete picture of the important physics. However, recent advances in instrumentation and digital computer-based DAQ now provide an opportunity to obtain full-field temperature, flow velocity and void fraction measurements with unprecedented temporal and spatial resolution. Future research should emphasize the use of advanced instrumentation and digital DAQ technologies to obtain these full-field measurements during convective condensation processes. From this, a database of experimental measurements can be created that will provide a more complete understanding of the mechanisms of convective condensation processes. This will greatly enhance efforts to develop better predictive modeling of heat and mass transport in such processes. Design of convective condensation experiments that embody this full-field measurement strategy can make use of the NASA FBCE or the FIR facility on the ISS. Experiments should incorporate an interdisciplinary approach that addresses multiple research questions in a single investigation. For example, a heat exchanger system with temperature-responsive switchable wettability could be paired with a study on how wettability influences capillary sloshing.

Although the size and fluid compatibility issues limit the utility of these two test rigs, many important studies can still be accomplished. Another example would be a spectrum of convective condensation experiments with different fluids, pressure conditions and flow rates that are selected for their relevance to important applications. The resulting data could be analyzed by multiple investigators to explore multiple topics from the following list: interfacial wave effects, inlet superheat or subcooled outlet effects, nanostructured and microstructured surface enhancement techniques, tapered channels, flow, dropwise condensation, pulsatile flow effects, and the effects of noncondensable gases (NCGs). The data from such experiments and subsequent improvements in modeling of the mechanisms will greatly enhance the body of scientific knowledge for convective condensation and aid in the design of more reliable, high-performance two-phase loop thermal management systems, vapor-compression cooling systems, and Rankine power systems.

2.4.3 Low-Gravity Justification

In convective condensation processes, gravity affects the flow by preferentially transporting the liquid phase in the direction of the gravity body force. Consequently, the two-phase flow morphology near the cold passage wall, the interaction of liquid with microstructures at the wall, interfacial waves, the resulting steady heat transfer, and transient behavior of the condensing process, are acutely affected by gravity. Instabilities in parallel channel condensers, like run-back, manifold, and liquid-leg, are more likely to occur without the stabilizing force of gravity. Fully stable condenser designs for low-gravity environments with higher pressure drops need to be developed and optimized for heat transfer and fluid power. Currently, long-duration convective condensation data in microgravity is not available, and lunar and Martian partial-gravity data is also lacking yet this would make it possible to develop more accurate models of the mechanisms of convective condensation and design of condensers for a wide variety of space and terrestrial applications. Multichannel condensers also have not been tested in long-term stable low gravity, so an important validated design tool to full size systems is currently needed. Long-duration experiments are key to developing a full understanding of the physics of convective condensation, and long-duration testing of new condenser design concepts in microgravity environments similar to those anticipated for space applications is the most definitive way to verify their performance capabilities and reliability.

2.4.4 Terrestrial Applications

In two-phase flow loops for thermal management, vapor-compression air-conditioning and refrigeration systems, and Rankine-cycle power systems, convective boiling and condensation processes occur in tandem, and are equally important to the overall efficiency and reliability of the system. As a result, much of what was stated previously regarding the importance of flow boiling research to terrestrial applications also applies to flow condensation research. The convective condensation research discussed here has the potential to open up new technologies that may foster development of high-performance, next-generation systems in the multibillion-dollar electric power, building air-conditioning, and electronics industries. The vapor compression cooling systems used for building air conditioning use a convective condensation process to reject heat and return liquid refrigerant to the evaporator, thereby sustaining the air cooling process. The energy efficiency of this type of widely used system will directly benefit from technologies developed from this research that enhance the effectiveness of convective condensation processes. In addition, development of new nongreenhouse-gas refrigerant working fluids for such systems is an important challenge for the next decade. Future experiments should include discussions of alternative working fluids and their benefits. Microgravity and partial-gravity convective condensation research will contribute to the development of next-generation refrigerants that transfer heat more efficiently in the boiling process and minimize global warming effects. Enhancement of steam condensers for electric power generation plants will improve system efficiency, thereby reducing electricity cost and environmental impact per kWh, and reducing the need for water spray cooling of condensers, which will allow better use of scarce water resources. A two-phase pumped loop is also recognized as an efficient system for removing heat at high heat flux levels from compact electronic devices, as discussed in a separate section on two-phase system behavior. A high-performance condenser is important to the success of such systems. Improved strategies for implementing compact condensers for electronic cooling systems may facilitate important advances in the compactness and power of microprocessors and other electronic devices. Future low-gravity flow condensation research will be particularly valuable to development of microcondensors and minicondensers for electronics cooling that are insensitive to changes in the g-vector environment for aircraft or ground vehicle applications. The broad impact of this research on the important industries discussed in this section is particularly noteworthy.

2.4.5 Benefits to NASA

Flow condensation processes are critically important to the efficient and safe operation of spacecraft human life-support systems for thermal management systems in power conversion and avionics that use two-phase pumped or capillary loops to take advantage of their lightweight and high-performance capabilities. Convective condensation also would be a centrally important mechanism for heat rejection in a Rankine power system for long-duration space exploration missions. The improved knowledge of the physics and improved modeling of convective condensation resulting from this research will facilitate the design of high-performance, high-reliability condensers for spacecraft applications, and will contribute to deeper understanding of the behavior of important systems in space environments. These types of systems, in which convective condensation processes play an important role, are central to the success of future human and robotic exploration.

2.4.6 Significance and Impact

The full-field, more highly resolved data obtained in the recommended research will provide a deeper understanding of the key mechanisms of convective condensation, associated instabilities, and NCG management. This microgravity data will facilitate development of more accurate models and design of more efficient systems with higher reliability and safety. The use of advanced instrumentation will be an innovative approach that will also foster the development of advanced tools and techniques to monitor and control convective condensation processes in terrestrial systems and systems for space applications. This may lead, for example, to smart sensor and control systems that monitor more detailed aspects of the condensation process and exercise a more sophisticated level of control that will enhance system efficiency. Smart systems of this type could open a pathway to a more sophisticated condenser-operating mode, such a pulsed-flow operation for enhanced efficiency, and they could provide improved reliability and safety of mission critical thermal management and power systems that use convective condensation processes. This research has the potential to strongly impact several applications communities: electric power generation, electronics cooling, building and automotive air conditioning, process refrigeration and green technologies such as solar thermal power and waste heat power generation. It has a strong potential to generate projects to develop new condenser technologies based on improved convective condensation processes in the applications areas previously described.

2.4.7 Research Partners

There are a wide variety of systems in which condensation processes play an important role, so naturally there is a broad spectrum of potential research partners for low-gravity flow condensation research. Because these condensation processes occur in tandem with flow boiling processes in vapor compression cooling systems, Rankine power systems, and pumped two-phase loops for thermal management, partners in low-gravity flow boiling research are also likely to be interested in microgravity convective condensation research as well. Potential partners may include electrical power producers (such as, Duke Energy Corp., etc.), the Electric Power Research Institute, companies in the building and automotive air-conditioning industries (Trane, Carrier, United Technologies Corp, GM, etc.), electronics and avionics companies (Intel Corp., Google, Hewlett Packard Enterprise, Honeywell International Inc., Collins Aerospace, etc.), and Government-funded research agencies connected to energy technologies and spacecraft thermal control (DOE, Department of Defense (DOD), DARPA, NRE, NREL, Lawrence Berkeley National Laboratory, Argonne National Laboratory, Glenn).

2.4.8 Facilities (New and Existing)

Facilities most likely to be used for low-gravity condensation research experiments are the FIR, FBCE (with or without modifications), ZBOT for low-heat flux research, and the MSG facility on the ISS.

2.4.9 Remarks

The RFI responses included one description of recommended research on condensation processes concerning container surface wettability and geometries.

2.5 Fundamentals of Vaporization and Condensation Physics

Rank: High Priority

2.5.1 Objectives

The research recommended in this topic category focuses on fundamental explorations of vaporization or condensation mechanisms. This research would complement the convective boiling and condensation research described previously by conducting more fundamental experiments, which would isolate phase-change mechanisms that drive the vaporization or condensation processes to allow them to be explored more deeply or under controlled conditions in the absence of gravity. This research is critical to developing and improving numerical models by providing closure laws and boundary conditions as well as providing benchmark test results for model validation. Because of the complexity of vaporization and condensation processes, this approach often makes it possible to more clearly distinguish important features of transport mechanisms. Of particular interest are fundamental studies of bubble nucleation in pure and fluid mixtures, vapor recoil instability, and dropwise condensation with or without gravity drainage on microstructured and nanostructured surfaces.

2.5.2 Scientific and Technical Merit

Strategically designed fundamental studies of vaporization and condensation mechanisms are expected to be among the most valuable research conducted as part of the microgravity boiling and condensation research program. This research requires high-fidelity instrumentation that captures local events within full-field data, thereby extensively documenting the smallest features of the mechanisms being studied. The key distinguishing feature of projects in this topic area is that they will be more focused and fundamental, and will aim to deeply probe critically important mechanisms of vaporization and condensation processes. The use of advanced instrumentation to obtain full-field data in a microgravity environment will be an innovative methodology for these fundamental studies of vaporization and condensation mechanisms. In particular, the advanced instrumentation together with long-duration experiments will allow exploration of transient boiling and condensation phenomena that could not be examined in short-duration tests with more limited instrumentation.

The capability for longer tests using more extensive instrumentation will facilitate design of experiments that can provide data to multiple investigators, thereby covering more research ground. These explorations of fundamental mechanisms of boiling and condensation will provide a deeper physical understanding of important mechanisms and an extensive experimental database that will enhance efforts to develop accurate models of boiling and condensation processes in general, and facilitate development of models that can be used to optimize these processes for important applications.

2.5.3 Microgravity Justification

In boiling and condensation processes, the two-phase system morphology near the heated or cooled surface is strongly affected by gravity. The liquid morphology in turn, affects virtually all the important mechanisms of these processes, ultimately having a very strong effect on the resulting heat transfer. The interaction of gravity forces with other mechanisms in the boiling or condensation process can be explored directly by conducting similar experiments with gravity forces present and under microgravity. Although microgravity boiling and condensation processes have been explored experimentally in a number of previous investigations, little long-term low-gravity experimental data are available. The proposed fundamental research would combine long-duration experiments with extensive advanced instrumentation to deeply explore fundamental mechanisms of boiling and condensation processes.

The experiments in the proposed research would target complex features of these processes (nucleation, bubble growth, interface stability, mass diffusion effects in multicomponent systems, bubble merging, Marangoni effects, etc.) under steady and transient conditions. Access to the long-duration microgravity environment is a key component of this research because it will allow better assessment of the interaction of gravity body forces with other flow and transport mechanisms. The resulting extensive experimental database from comparable experiments with and without gravity will advance fundamental understanding of the mechanisms of these processes, and the data will be extremely valuable to researchers developing mechanism models and design analysis tools for evaporators and condensers for terrestrial and space applications.

2.5.4 Terrestrial Applications

As noted in earlier sections, vaporization and condensation processes are critically important to Rankine-cycle power generation systems, vapor-compression air-conditioning systems for buildings and automobiles, refrigeration processes, electronics cooling and data center thermal management systems. The boiling and condensation research recommended here has the potential to foster development of innovative next-generation systems in the multibillion-dollar electric power, building air-conditioning, and electronics industries.

The energy efficiency of widely used vapor-compression air-conditioning and refrigeration systems will directly benefit from technologies developed from this research that enhance the effectiveness of vaporization and condensation processes. Microgravity boiling and condensation research will also contribute to the development of next-generation systems that use refrigerants that transfer heat more efficiently in boiling and condensation and minimize global warming effects. Enhancement of steam boiler and condensers for fossil fuel and solar-thermal electric power generation plants will enhance system efficiency, thereby reducing electricity cost and environmental impact, and reducing the need to use scarce water resources for water spray cooling of condensers.

The microgravity boiling and condensation research will also be particularly valuable to development of microcondensers and minicondensers for electronics cooling that are insensitive to changes in the g-force environment for aircraft or ground vehicles. The broad impact of this research on the important industries discussed in this section is indicative of a very strong potential return on investment for this research.

2.5.5 Benefits to NASA

Boiling and condensation processes are critically important to efficient and safe operation of spacecraft thermal management systems for human habitats and avionics that use two-phase pumped or capillary loops. These processes are also centrally important to cryogenic propellant storage systems for long-duration space exploration missions. The deeper understanding of key boiling and condensation mechanisms provided by this research will enhance development of high-performance pumped two-phase loop thermal management technologies as well as enable long-term storage and handling of cryogenic propellant systems critical for space exploration and applications. These types of systems, in which boiling and condensation processes play a critically important role, are central to the success of future human and robotic exploration. The improved knowledge of the physics and improved modeling of boiling and condensation processes resulting from this research will also significantly reduce the uncertainty associated with using systems employing boiling and condensation processes in space exploration.

2.5.6 Significance and Impact

The highly resolved, full-field data obtained in this research in long-duration low-gravity experiments for steady and transient processes will provide an increased understanding of the key mechanisms of boiling and condensation processes. The resulting extensive database will facilitate development of more accurate models of the mechanisms, which, in turn, will make possible the design of more efficient, more reliable, and safer thermal management, cryogenic propulsion storage, and power systems that make use of boiling and condensation processes. Building on the models of discrete phase-change events and processes, along with flow pattern and void fraction predictive models, phenomenologically correct correlations for entire tubes can be developed. These correlations can then be incorporated into system design and simulation. It may specifically lead to development of nanostructured surfaces that enhance boiling or condensation heat transfer, smart controls that can detect precursors to the onset of CHF conditions, working fluids mixtures that suppress the onset of CHF under microgravity, and more accurate models of boiling and condensation heat transfer that can be used to optimize high-performance designs for evaporators and condensers in applications.

The results of this research are likely to generate new projects to develop next-generation technologies in terrestrial applications like Rankine and solar-thermal electric power generation, building and automotive air-conditioning systems and thermal management of electronic devices and data centers. These applications areas are so expansive that if the results of this research impact even a subset of these applications, the effects in terms of economic impact and reduced use of energy resources and environmental impact would be huge. This research is synergistic with the efforts of DOE (Advanced Research Projects Agency-Energy ARPA-E) and NREL to develop more efficient, safer, and more reliable energy conversion technologies that have less environmental impact. The improved knowledge of the physics and improved modeling of boiling and condensation mechanisms resulting from this research will facilitate the design of high-performance, high-reliability evaporators and boilers for spacecraft applications, and will significantly reduce the uncertainty associated with using systems employing flow boiling in space exploration.

2.5.7 Research Partners

There are a wide variety of terrestrial and spacecraft systems in which boiling or condensation may play an important role. Vaporization and condensation processes occur in tandem in vapor-compression cooling systems, Rankine power systems, and pumped two-phase loops for thermal management and cryogenic propellants. Potential research partners may include electrical power producers (PG&E, Duke Energy Corp., etc.), the Electric Power Research Institute, companies in the building and automotive air-conditioning industries (Trane, Carrier, United Technologies Corp., GM, etc.), electronics and avionics companies (Intel Corp., Google, Hewlett Packard Enterprise, Honeywell International Inc., Collins Aerospace, Raytheon Technologies Corp., etc.), and Government-funded research agencies connected to energy technologies and spacecraft thermal control (DOE, NRE, NREL, Lawrence Berkeley National Laboratory, Glenn).

2.5.8 Facilities (New or Existing)

Facilities most likely to be used for microgravity fundamental vaporization and condensation research experiments are the FIR, the FBCE (with or without modifications), ZBOT for low heat flux, and the MSG facility.

2.5.9 Remarks

The RFI responses included seven descriptions of recommended research on boiling and condensation processes.

2.6 Two-Phase System Behavior

Rank: High Priority

2.6.1 Objectives

The objective of this work is to investigate the flow instability mechanisms in the two-phase systems in microgravity and partial-gravity conditions, which will lead to the development of dynamic models capable of predicting the system response accurately. The models will also guide the development of an active control strategy, which will modulate system inputs like pump speed and valve opening in real-time to ensure stable conditions even in the presence of transient heat loads.

Understanding two-phase system behavior in microgravity and partial gravity is crucial to safe system operation when such a system is used for thermal management, power delivery, or cooling on long-duration missions, which encompass lunar and Martian missions. Understanding two-phase system behavior involves two aspects and necessitates testing and modeling. The proposed research in this category involves performing experiments that can directly be used in modeling and system behavior prediction. Instabilities that can compromise the behavior of a two-phase system are numerous and experimental research that directly addresses instabilities and the system level modeling that utilizes the findings from the experimental research will be a valuable asset for system level performance and reliability prediction. Density wave oscillations is an instability that occurs in boiling two-phase fluid systems steady-state and results in oscillations between 0.1 to 1 Hz with the oscillation amplitude saturating at an asymptotic value. The use of microchannel heat exchangers in terrestrial systems can cause flow instabilities such as Ledinegg instability, flow maldistribution, and pressure drop oscillations. Other instabilities may result from start-up transients, loss of coolant effects, effects of NCGs, phase separator operation, and control strategies. These instabilities can result in structural vibration, fatigue, system failure, and CHF, making the overall heat transfer very inefficient. The reduced heat transfer can cause a steep increase in surface temperature, which can cause the failure of the cooling system. These same instabilities that occur in terrestrial systems are prone to take place in two-phase microgravity and partial-gravity systems where flows depend on shear and capillary forces and partially on gravitational body forces.

Systems that are built for phase-change heat transfer are generally either pumped-liquid or vapor-compression cycles. Typical two-phase systems consist of an evaporator and a condenser, a mechanical device that can be either a pump or a compressor, an accumulator or storage tank for accommodation of fluid expansion and valves for flow expansion or flow controls, and the diagnostic instruments like flow meters, pressure transducers, thermocouples, and visualization accommodations such as normal and high-speed cameras. Proposed research focuses on using two-phase flow systems equipped with diagnostics to understand instabilities induced by combinations of operating conditions in microgravity and partial-gravity environments. Experiments will aim to quantify the effect of boiling surface roughness and wettability, pressure drop, and thermal performance that will aid in the development of predictive models on the system level. These conditions will result from a wide set of parameters with a subset of these parameters resulting in unstable behavior which will be recorded, analyzed, and predicted by the system level analyses.

Another topic of research effort is the stability of vapor-compression refrigeration systems in microgravity and partial-gravity environments. Research will focus on first verifying the performance of a vapor-compression system in such an environment, and second on understanding system instabilities in a refrigeration system. Proposed research will require the buildup of a vapor-compression refrigeration cycle that will be heavily instrumented in the evaporator, condenser, expansion valve, and compressor with observational and sight glass used for observing and understanding the flow quality. The research will focus on testing the vapor-compression system in microgravity and under partial-gravity conditions. System level investigation of instabilities will encompass testing at test conditions that will bring forth a particular instability. These conditions will be incorporated in the predictive model and validated accordingly. Heating and cooling two-phase fluid systems are crucial for understanding system level instabilities.

The basic mechanisms of boiling and condensation at a local scale are generally dependent on the magnitude and direction of the ambient gravitational field. Highly inertial flow fields are less dependent on gravity because the shear effects dominate both gravity and capillary forces. In addition to high-shear flow, curvilinear channels have also been used to provide a flow field that is less sensitive to gravity. Some two-phase microgravity systems can be designed to be less gravity dependent by using shear and centripetal forces. However, the transition criteria for gravity independent flow regimes can be established in gravity assisting, gravity neutral, and unfavorable gravity orientations on Earth for both heated and refrigeration cycles. After ground testing, the threshold criteria must be verified in orbital testing.

2.6.2 Scientific and Technical Merit

In order to understand gravity independence of fluid systems and instabilities, the effect of gravity at the component and system level must similarly be investigated. Also, fluid system architecture and placement of fluid system components must be studied experimentally and by modeling in order to assess flow instabilities. Pressure drops, heat transfer, and void fraction are dependent on gravity. Different flow patterns drive changes in pressure drop, liquid hold-up, and system inventory. A favorable gravity orientation generally assists most phase-change flow systems, for example, boiling in the upward direction and condensing in the direction of gravity. The knowledge to design systems for microgravity can only be gathered from orientation dependent testing with model development based on these data and validation of those models in microgravity. Experimental exploration of systems issues in microgravity will provide critical insight into the mechanisms of system behavior, and facilitate development of models of the mechanisms that can be used to develop high performance, reliable, and safe systems for space applications. The experimental exploration of system issues would emphasize use of extensive advanced instrumentation and DAQ, and target potential system issues such as flow instabilities, start-up transients, loss of coolant effects, effects of NCGs, phase separator operation, and control strategies. The experimental studies can explore problematic operating conditions and try out modification strategies to mitigate them. There are no obvious technical barriers to this strategy for exploring microgravity system issues. Recent development of new instrumentation techniques (e.g., microparticle image velocimetry instrumentation, high-speed video cameras and image analysis software, and calibrated infrared cameras) and high-speed DAQ provide an unprecedented opportunity to obtain high-quality system transient data that are highly resolved spatially and temporally. Experiments of this type could make use of the FIR, FBCE, or the MSG facility, and the experiments could be designed to provide full-field data that can facilitate an interdisciplinary approach that addresses multiple research questions in a single investigation. The data from such experiments and subsequent improvements in modeling of the mechanisms will greatly enhance the body of scientific knowledge regarding two-phase system performance in microgravity environments, and aid in the design of more reliable high-performance two-phase loop and Rankine power systems that utilize phase-change fluids.

2.6.3 Microgravity Justification

The proposed research in this topic area will focus on component and system level behavior that are likely to arise in space systems operating in microgravity environments. Experimental study of issues and problems associated with phase change and phase separation equipment in systems for microgravity must be tested and models validated in long duration experiments in the microgravity environment itself. Comparison of the system performance under microgravity conditions to models developed from normal gravity testing will confirm the models for system operation in all gravity environments. The understanding of the mechanisms underlying the system behavior therefore will foster the development of better models of system behavior mechanisms that will facilitate the design of more efficient and reliable systems for spacecraft applications that employ boiling and condensation processes.

2.6.4 Terrestrial Applications

Although the motivation for most of the low-gravity boiling and condensation systems research will relate most directly to systems designed for spacecraft application, results for this research will also provide a deeper understanding of comparable terrestrial systems under similar conditions. The nuclear power industry, the Rankine-cycle-based (fossil and solar-thermal) power industry, and the chemical process industry would have strong interests in studies of two-phase system behavior under microgravity because comparison with normal gravity behavior would provide insight into how gravity affects system issues like startup transients, flow instability, NCG separation and removal, loss of coolant, and transients due to load variation. Enhanced design and control strategies for two-phase systems that are developed in the low gravity system experiments and modeling research recommended here are likely to lead to improved system technologies in the power and process industry applications areas previously described.

2.6.5 Benefits to NASA

The better understanding of key system behavior mechanisms provided by this research and the development of better models of system behavior in a microgravity environment will enhance the design and development of two-phase pumped loop thermal management technologies, liquid fuel propulsion systems, and Rankine power systems for space applications. This research will contribute to deeper understanding of the behavior of systems in the space environment. It is research that is uniquely needed by NASA and strongly complements NASA's mission portfolio. Successful design and implementation of these types of system are central to the success of future human and robotic exploration.

2.6.6 Significance and Impact

Experimental exploration of two-phase boiling and condensation system issues in microgravity will provide a deeper understanding of the mechanisms of system behavior and facilitate development of accurate models of the mechanisms. The recommended experimental exploration of system issues would emphasize use of extensive advanced instrumentation and DAQ, and target potential system issues such as flow instabilities, start-up transients, loss of coolant effects, effects of NCG, phase separator operation, and control strategies. System design to reliably handle these issues is critical to the efficient, safe, and reliable operation of two-phase systems in space applications. The experiments can be designed to explore problematic operating conditions and try out modification strategies to mitigate them. In doing so, the experiments will establish the limits of satisfactory operation for a targeted type of microgravity system. The detailed system model developed for design of the microgravity two-phase systems can be preliminarily validated with terrestrial experiments and will become a correlating tool for in-orbit operation. Instability effects can be explored with the system model. Recent development of new instrumentation technologies and high-speed digital DAQ provide an unprecedented opportunity to obtain high-quality system transient data that are highly resolved spatially and temporally. Experiments of this type could make use of the FIR, FBCE, or MSG facility. System experiments could be designed to provide full-field data that can facilitate an interdisciplinary approach that addresses multiple research questions in a single investigation. This research will provide a deeper understanding of key mechanisms of two-phase microgravity system behavior. The results will facilitate development of better modeling of these mechanisms and greatly enhance capabilities to design two-phase systems for space applications that maximize efficiency, reliability, and safety. The results of this research will also contribute to innovative technology improvements in terrestrial industries that work with two-phase flow systems for power and chemical and petroleum process applications.

2.6.7 Research Partners

Nuclear and fossil fuel electrical power producers (Electric Power Research Institute, PG&E, etc.), companies in the building and automotive air-conditioning industries (Trane, Carrier, United Technologies Corp., GM, etc.), process industries (Dow, Monsanto Co., Allied Chemical Corp.), electronics industry companies (Intel Corp., Dell, Hewlett Packard Enterprise, etc.), companies in the chemical and petroleum process industries (BP PLC, Chevron Corp., ExxonMobil Corp., etc.), DOE, NREL, NRI, Lawrence Berkeley National Laboratory, and Glenn.

2.6.8 Facilities (New or Existing)

Facilities include the FIR, the FBCE (with or without modifications), ZBOT for low-heat flux, and the MSG facility.

2.6.9 Remarks

The RFI responses included six descriptions of recommended research on boiling and condensation processes.

2.7 Instrumentation, Diagnostics, and Facilities

Rank: High Priority

2.7.1 Objectives

Numerical simulations, numerics, can provide insight into the physics of phase change and is slowly becoming a cost-effective way to design new systems involving boiling and condensation in heating, ventilation, and air conditioning (HVAC) and power systems, cryogenics, and water recovery among others. However, the models that feed into the numerics should be validated and experiments and simulations should ideally be tightly coupled, with experiments providing the needed boundary and initial conditions required for simulations, and simulations providing insight into experimental results. Advanced diagnostic techniques are needed to verify phase-change heat transfer mechanisms for models and theory. Ideally, full-field measurements of the velocity and temperature within the fluid (both vapor and liquid) along with wall temperature distributions would be measured. Some techniques to measure the temperature and heat flux distributions at the solid and fluid interface have recently been developed using various techniques, but measurements within the fluid have proved to be very difficult especially at higher heat fluxes due to the merging and departing bubbles that limit optical access. High resolution tomographic techniques based on electrical conductivity, electrical capacitance, nuclear spin, neutron absorption, etc. may provide a way to access such data. Techniques to measure the thickness of thin films that occur in the annular regime in flow boiling or condensation are generally based on optical or ultrasonic techniques that are available, but these are not reliable when used to measure highly turbulent, wavy films. More robust techniques to measure film thicknesses are needed.

Data taken over a continuous range of gravity levels between terrestrial gravity and microgravity has proved vital to the understanding of gravity effects on pool boiling through the identification of at least two regimes (a buoyancy dominated regime and a surface tension dominated regime). Similar regime changes with their corresponding impact on heat transfer are fully expected to occur as gravity changes in flow boiling. Changes in flow regime with corresponding changes in heat transfer mechanisms occur as inlet and boundary conditions are changed, and these flow regime boundaries as a function of gravity need to be mapped if a fundamental understanding of gravity effects is to be understood. The effect of gravity within a given flow regime will also need to be determined.

A long-term human presence on the Moon and eventually on Mars will require two-phase systems that can operate reliably under fractional gravity levels. The performance of these systems generally decreases with gravity, and data quantifying any changes in performance is needed. The performance prediction requires a sufficient heat transfer database and reliable models, both of which are not currently available. Some of the important parameters to be varied include fluid, mass flux, tube diameter and length, tube shape and orientation, wall heat flux, nucleation site density, and fluid subcooling.

2.7.2 Scientific and Technical Merit

Ready access to experimental facilities that enable measurements to be made under varying gravity conditions, including microgravity, will be crucial to understanding and validating the conditions under which two-phase system instabilities occur under terrestrial, Martian, lunar, and microgravity experiments. Fundamental aspects of these experiments will greatly enhance the body of scientific knowledge regarding boiling, and the improved modeling that results from them will aid in the design of engineering systems utilizing phase-change fluids that range from liquid metals to cryogenic fluids.

The use of advanced instrumentation and DAQ systems to obtain full-field data for pool and flow boiling processes, and improved modeling that will be developed from such data, will have a game-changing impact on this field. This research will provide a valuable dataset for model development and will significantly improve our understanding of boiling physics. Future experiments should provide spatially and temporally resolved wall heat flux measurement whenever possible. Techniques that can access velocity and temperature within the bulk fluid should be developed and demonstrated.

2.7.3 Microgravity Justification

Gravity can change the morphology of the two-phase flow by preferentially skewing the liquid phase distribution in the direction of the gravity body force acting on the fluid. The morphology of the two-phase system profoundly affects the primary mechanisms of the boiling process. Consequently, liquid replenishment and vapor removal from the heating surface, the resulting heat transfer, transients leading to CHF, and two-phase flow instabilities are strongly affected by gravity. Full-field data for long-duration flow boiling in stable microgravity or partial gravity do not exist, and is essential to accurate modeling of boiling processes and design of devices and systems in which boiling occurs. Long-duration boiling experiments are vital to development of a more complete understanding of boiling physics, and steady-flow, long-duration testing of new evaporator design concepts at operating conditions anticipated for applications is the best way to verify their performance and assess their reliability.

2.7.4 Terrestrial Applications

Advanced instrumentation developed for two-phase flow diagnostics in microgravity and partial gravity would be widely and immediately applicable to research into terrestrial systems such as oil and gas flows, loss of coolant accidents in nuclear reactors, heat pipes, fuel cells, electronics cooling, HVAC systems, etc. The improved understanding of phase-change mechanisms can be used to tailor surfaces and conditions to increase heat transfer equipment efficiency.

2.7.5 Benefits to NASA

The advanced instrumentation and the resulting improvement in our understanding of phase-change mechanisms can lead to compact, low-mass heat exchangers with greatly improved efficiency. Launch costs can be lowered or larger and heavier payloads can be accommodated due to lower heat exchanger mass and volume.

2.7.6 Significance and Impact

Full-field data will provide tremendous insight into the physics of two-phase flows, leading to advances in technical capabilities. Such data can be used to provide benchmarks for numerical simulations, and eventually enable virtual design of heat exchangers to be performed reliably.

2.7.7 Research Partners

Research partners potentially interested in developing advanced instrumentation include NSF, oil and gas firms, the nuclear industry, and private companies. Small Business Innovation Research grants (SBIRs) may be a promising avenue for developing the needed instrumentation.

2.7.8 Facilities (New or Existing)

Aircraft are used to produce low- ($\sim 10^{-2}$) and partial-gravity levels for limited times (~20 s) and have been very useful for obtaining preliminary data. Flights dedicated to partial-gravity experiments are relatively rare, however.

Drop towers can perform microgravity experiments at much lower cost than aircraft and are much more accessible, but the 2 to 5 s drop time is often a limitation to obtaining steady state data. Longer duration (10 to 20 s) drop towers that provide high quality microgravity as well as fractional gravity conditions would be a relatively low-cost way to explore boiling behavior over a wide range of conditions that would quickly advance our understanding.

Facilities in which future space experiments can be conducted in an interdisciplinary approach include the FIR and the FBCE on the ISS. FBCE is being designed so the test section can be replaced in-orbit.

2.7.9 Remarks

The RFI responses included two descriptions of recommended research on instrumentation, diagnostics, and facilities.

3.0 Topic Area Report: Water Recovery

Submitted by:

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NASA Marshall Space Flight Center

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3.1 Purpose of Session

The purpose of the water recovery breakout session was twofold, including identification of areas in which additional research and development (R&D) will improve the community's fundamental understanding of multiphase fluid physics in microgravity while also identifying known design issues associated with multiphase fluids that can potentially be addressed through further technology development. Potential gaps in fundamental fluid physics were previously identified in the 2018 National Academies report "A Midterm Assessment of Implementation of the Decadal Survey on Life and Physical Sciences Research at NASA" (Ref. 1). Various aspects of these phenomena were discussed during the session. Subsequently, current known issues with the water treatment system on the ISS were reviewed followed by discussion on how advancements in multiphase fluid physics could be used to resolve or mitigate the design issue. The intent for the discussion in this session was to use the NASA Research Announcement process to pursue an improved understanding of multiphase fluid physics in microgravity along with the intended application toward specific design issues currently facing water treatment on and beyond the ISS mission.

3.2 Summary and Recommendations

Representatives from NASA, academia, and industry discussed various aspects of multiphase fluid physics relative to water treatment in microgravity and partial gravity. Of the seven RFIs submitted, six were reviewed by the submitter during the session while the remaining RFI was reviewed by the key personnel with knowledge in the subject matter. More information on these RFIs is provided in the following information. The subsequent discussion within the session initially focused on improving the fundamental understanding of multiphase fluid physics in microgravity, but also addressed known issues with the current water treatment system on the ISS. The participants recommended funding research in the areas of fluid physics defined in Reference 1 while also including specific applications toward the known performance issues associated with multiphase physics on the ISS. By improving our collective understanding of multiphase fluid physics, key personnel will possess more expertise that may be applied to future technology design and toward understanding of performance issues that may occur on the ISS or subsequent NASA missions. In addition, technology development toward known design issues provides incentive to improve the critical and focused understanding of fluid physics in microgravity beyond the current fundamental understanding. These two facets should complement each other as priorities in future R&D.

3.3 RFI Summaries

Eight submitted RFI's were applicable for this breakout session.

3.3.1 Harvesting Water Vapors in the Air

The scope of this concept is to harvest small amounts of water vapor in air using a vibrating mesh system. This was inspired by lobster using their antennae to disturb water flow by shaking their antennae to sense chemicals. The specific process is to collect water vapor (gas phase) not liquid drops. A carrier gas flows through the vibrating mesh at a low Reynolds number flow. Because the vibrating mesh disturbs streamlines, dust particles are captured. The mesh is vibrated at about 100 Hz to capture dust particles. While it is not clear from the written RFI submitted whether water vapor or water drops was being discussed, it was clear in the breakout session discussion that the idea was to capture water vapor and not liquid drops. In order to capture water vapor¸ the frequency of the mesh vibration needs to be determined. The 1g studies will involve humid air introduced in a wind tunnel.

3.3.2 Three-Phase Microgravity Slurry Reactor for Water Reclamation

A slurry reactor is proposed to replace current packed bed catalytic reactor in the ISS water reclamation system. Slurry bed reactors can increase useable surface area by reducing preferential flow caused by gas phase and/or bubble blockage and by allowing small particle size. Because particles move in the flow, slurries may have more surface area for catalytic reactions even for low particle loading. Moving particles lead to better mixing and enhanced mass transfer. For Stokes number (for particle motion) >1, Reynolds number >1 particles do not follow streamlines. The study wants to look at transport in the inertial regime; the rheology of the suspension in such regimes is unknown and thought to be a fundamental investigation. Integration of slurry phase reactors with vortex separators may facilitate required phase separation.

There is general agreement that mass transfer might be limited in packed beds and the enhancement brought about by slurries would be beneficial. The chief issues with slurries in microgravity include:

- Generation of fines due to particle collision and abrasion.
- General management of the solid particles added or removed in the experimental hardware and ensuring they flow well in the test section and reactor.
- Whether consistency of distribution of particles within the reactor might be important.

The general consensus appears to be that slurries might be an important fundamental research area and knowledge gaps exist to predict performance and operation. These studies are also not possible in 1g due to required Stokes and Reynolds number.

3.3.3 De-emulsification of Recovered Water Using Three-Dimensional Printed On-Demand Process Enhancements

The idea is to study three-dimensional printed (3dp) "membranes" for water purification. It was pointed out that 3dp membranes can be used to control pore size and surface functionality and could be useful in producing reactive packed beds for treatment or synthesis and possibly for de-emulsification.

There was minimal discussion of this topic. A question was asked about pressure drop through the 3dp membranes. That was not addressed but was stated that membranes can withstand 100 bar pressure across them.

3.3.4 Water Recovery in Space

The idea is to use solar energy, waste heat, etc., in conjunction with novel materials to distill and purify water. There was no further discussion of this idea.

3.3.5 Bubble Coalescence and Displacement in Porous Media Operations in Microgravity

The study of bubble coalescence and bubble removal in packed beds was proposed. In some packed bed reactor experiment tests, bubbles coalesced and occupied a large portion of the test section. Bubble coalescence and consequence on liquid holdup under various conditions are of interest and currently not able to be adequately modeled. An improved understanding of coalescence and trapping is needed to further advance mitigation strategies.

3.3.6 Understanding Evaporation Near Kinetic Limits

This submitted RFI focused on using kinetic theory to calculate interphase mass flux for a pure substance. Using the expression derived by Shrage (Ref. 2), a critical parameter that also affects interfacial kinetics is the mass accommodation coefficient. With interphase mass flux being linearly proportional to the accommodation coefficient, knowing this parameter is critical. The interface limits the overall kinetics, which can allow the quantification of the accommodation coefficient. A carefully planned experiment will also allow testing the integrity of the expression of interphase mass flux derived from kinetic theory. Such an investigation may use data from a combination of high-speed imaging, infrared thermography, and measurements of vapor pressure. The author of this RFI was not present in the session; therefore, this topic was not discussed.

3.3.7 Superhydrophobic Surfaces to Condense and Collect Water

Nanostructured coatings on cooling surfaces and patterned coatings can improve condensation rates by reducing formation of liquid thin films and help manage condensation formation on surfaces. Superhydrophobic surfaces will prevent liquid film development and force drop formation increasing condensation rates. Patterning can be used to transport liquid to facilitate water collection. Presumably dropwise condensation is promoted leading to more efficient condensation. Challenges to implementation included water collection from surfaces and coating life.

3.3.8 Multiuser Facility for Two-Phase Flows

A multiuser flight facility that can be implemented on a short timeline using flight approved subsystems was proposed to study multiphase flow issues. The facility would support an interchangeable test article allowing multiple types of experiments. It was suggested that many of the ideas presented in the RFIs could be implemented in devices that are used as test cells in the proposed facility. In general, the idea was well supported as it allows flexibility to research multiple multiphase flow issues. Discussion centered on being able to vary parameters such as viscosity, liquids other than water, interfacial dynamics and waves, and nonequilibrium regimes occurring during startup and shutdown.

3.4 Near Term Applications

Three applications of research dealing with problems and a hardware concept were discussed.

3.4.1 Uncontrolled Condensation and Fluid Management

Uncontrolled condensation can impact operation of multiphase systems. The distillation assembly currently experiences condensation in the stationary bowl. This is currently managed by surface heaters to evaporate condensation as it occurs. The heaters increase power consumption while also reducing the efficiency of the distillation process by increasing the temperature in the evaporator. Possible solutions included controlling condensation locations, contouring the surface of the outer shell to produce capillary driven flows, and/or using surface modifications (e.g., superhydrophobic surface patterning) to transport water to collection points. While the current state of knowledge was deemed sufficient to develop solutions assuming hardware changes are allowed, transient conditions during startup may be less able to be modeled and therefore introduce uncertainties. Research focused on predicting and controlling condensation points coupled with fluid flow management would be useful for both current hardware and future improved hardware designs.

3.4.2 Fugitive Bubble Capture

Removal of fugitive bubbles upstream of the ISS Water Processing Assembly waste tank would prevent loss of liquid storage volume in the waste tank and allow relocation of the mixed beds upstream to minimize biofilm growth in the waste tank. Microbial growth in the waste tank produces issues for downstream systems. Removal of substrates and nutrients would limit growth but relocation of multifiltration beds to remove nutrients and substrates upstream of waste tank requires the addition of a prefilter. Due to occlusion of fugitive bubbles, implementation of a prefilter is challenging. Possible solutions to remove fugitive bubbles included passive capillary-based phase separators and acoustic waves to guide bubbles. Current state of knowledge was deemed sufficient to address the capillary separator, but a need was seen to understand and support the design of acoustic bubble separators.

3.4.3 Vortex Separator

There are fundamental issues with vortex separation in microgravity that prevent its inclusion in flight hardware. Better model development and knowledge basis is needed to understand: (1) momentum coupling from single and multiphase tangential jets (2) bubble breakup, entrainment, transport and coalescence and (3) thermal and mass transport models.

Additionally, better instrumentation is needed to study vortex separation as the current understanding is based only on system pressure and video data.

3.5 Reduced Gravity Justification

During the session, participants discussed the significance of partial gravity on fluid physics, and whether partial gravity should be a primary focus during the workshop. The participants agreed that partial gravity has negligible impact for applications in which only a single phase is present, consistent with treatment processes in microgravity. However, similar to microgravity, multiphase applications do exist that are more sensitive to reduced gravity and may be appropriate for further research and focused development. The general consensus is that the presence of even partial gravity can ultimately allow the component design to take advantage of physical treatment processes used on Earth to achieve phase separation or effective mass transfer, but the fundamental understanding of how partial gravity impacts these processes is not accurately defined. More specifically, the reduction in interfacial shear and the mixing that it encourages within the phases necessitate a need to better understand how two-phase flow in reduced-gravity impacts mass transfer.

Treatment processes involving multiphase flow face notable design challenges because of the unique liquid and vapor and liquid and solid configurations and phase distributions that occur in the absence of gravity. In reduced gravity, a new balance comes into play between inertial and interfacial forces with the lessening of buoyancy forces, so that the mechanics of the flow are measurably altered. One consequence is the unidirectional motion along the gas and liquid interface increasing the amount of bubble coalescence. While the fundamentals of coalescence are known and can be used for engineering design, a more theoretical understanding of coalescence is needed. The reduction of interfacial shear in a reduced-gravity environment provides an opportunity to elucidate this behavior.

One manifestation of the inertial effects is that the smaller density of the gas phase compared to the liquid phase enables the gas phase to turn corners quicker than the liquid phase. This principle is used for phase separators at faster flow rates while capillary-based techniques can be used for slower flows. It is necessary to bridge the gap between these two regimes by examining other techniques such as acoustics.

Another area of unique concern is laundry and hygiene waste streams. These waste streams have not been generated in microgravity because of the technical challenges associated with their design relative to the inherent benefit. However, laundry and hygiene is expected to be part of the nominal architecture in a partial-gravity application, given the simplified approach to waste water generation in partial gravity. However, this approach does introduce the additional complexity associated with surfactants and the resultant generation of foam. Foam stability in partial gravity is a critical factor in the collection and treatment of these waste streams; therefore, it is critical to improve the understanding of the fundamental mechanics associated with the formation and destruction of foam.

Specific areas to be considered include the following. First and foremost is gas and liquid phase separation, in which a simple settling tank may be implemented in partial gravity. However, the effect of partial gravity on the required residence time must be understood to ensure sufficient residence time is provided to achieve phase separation. Depending on that answer, active phase separation (rotary or passive membrane) may still be more desirable even in a partial-gravity application. Next, gas occlusion in intended two-phase flow (e.g., a thermal catalytic reactor that uses gaseous oxygen) will be measurably different in partial gravity than normal gravity, and understanding this effect is necessary to ensure effective distribution of the oxygen to the reaction sites. In this same treatment process, mass transfer will also be variant in partial gravity, though this is not considered to be a significant effect because the fluid flow would still be the driving force to ensure effective mass transfer of oxygen to the reaction sites. Another treatment process that will be impacted in partial gravity is reverse osmosis, which has been shown to exhibit significant degraded performance in the absence of gravity due to concentration polarization. This effect will be enhanced in partial gravity, though additional research would be necessary to characterize the fundamental mechanics to support an adequate treatment design. Finally, liquid and solid phase separation will also be impacted by partial gravity. In partial gravity, solids may be effectively removed by allowing sufficient residence time, whereas in microgravity these same solids will not be removed from the liquid flow stream. However, it is critical that researchers understand the additional residence time required as a function of the reduced gravity.

In summary, participants agreed that partial gravity may greatly simplify treatment processes that require more complicated engineering (e.g., rotary separators) in the absence of gravity. However, improving our fundamental understanding of the fluid mechanics in partial gravity is critical toward understanding how to take advantage of partial gravity.

3.5.1 Prioritization of Research Areas

The current water treatment system on the ISS produces potable water from crew urine, humidity condensate, and Sabatier product water. This system has been operational since late November 2008, exhibiting sound performance though not without anomalies. The specific treatment processes implemented for multiphase fluid control have worked as intended, including mechanical filtration for solids removal, rotary separators and passive membrane separators for removing free gas from process water, and the urine distillation process in which water is evaporated from urine and subsequently condensed to form urine distillate. However, there have been anomalies when multiphase flow has occurred when not intended, including precipitation of solids in the urine distillation process, condensation in the stationary bowl of the distillation assembly, biofilm growth in the Water Processor Assembly waste tank, and free gas in the Water Processor Assembly product tank. These anomalies have been satisfactorily addressed on the ISS, though further technology development may improve the system performance on the ISS. In some cases, technology development may be required for exploration beyond the ISS to ensure a robust design solution. As such, credible design solutions that would address any of these problem areas would be considered the highest priority.

Though key personnel have improved our collective understanding of fluid physics in microgravity, significant gaps remain in the field of multiphase fluid flow. These gaps have been previously defined in NASA's 2018 Decadal Survey (Ref. 1). Further research toward improved understanding of multiphase fluid physics is a high priority to enable future design concepts while providing key personnel with critical knowledge that may be used to address future performance anomalies. Though fundamental research is listed as the second priority, it must be emphasized that a critical breakthrough in multiphase fluid physics may be ranked higher than technology development for a specific application based on the panel's understanding of the viability of the proposed research and its ultimate value to NASA.

The next priority is the fundamental improvement of current technologies implemented on the ISS. Though current technologies (rotary separators, passive membrane separators, catalytic reactor, and urine distillation) have functioned as designed on the ISS, it is desirable to improve these technologies using additional understanding of multiphase fluid physics. For example, replacing a rotary separator with a vortex separator is desirable because it eliminates reliability issues with a rotating part. However, this approach must demonstrate that the vortex separator meets the performance requirements over the entire operational range for the given application.

An additional area for further research involves new technologies for water treatment in microgravity. Though the ISS water treatment architecture is the baseline for subsequent NASA missions in microgravity, NASA continues to pursue any new technologies that may upgrade this architecture, either by reducing system and consumable mass or improving the system reliability. These new technologies (e.g., biological reactor, super critical water oxidation, and electrochemical oxidation) may introduce new or unique issues associated with multiphase fluid flow that must be addressed to advance that technology as a viable upgrade to the current system employed on the ISS. As such, the next funding priority would be research that may validate the technology by demonstrating successful function of multiphase fluid physics in microgravity.

Finally, NASA is currently evaluating various water treatment technologies for a partial gravity (i.e., lunar and Mars) application. Though partial gravity simplifies the phenomena associated with multiphase flow, the personnel in the session agreed that reduced gravity may impact the performance of critical technologies to the point that further research may be necessary.

3.6 References

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4.0 Topic Area Report: Heat Pipe

Submitted by:

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4.1 Purpose of Session

The purpose of this session was to discuss fundamental and applied microgravity research required so that NASA could field advanced heat pipes to support its manned and unmanned exploration missions. A number of passive, two-phase devices were discussed including:

- Constant conductance heat pipes (CCHPs)
- Variable conductance heat pipes (VCHPs)
- Loop heat pipes (LHPs) and capillary pumped loops (CPLs)
- Oscillating heat pipes (OHPs), also known as pulsating heat pipes (PHPs).

The discussion was divided into two broad areas:

1. Heat pipe fundamentals
2. Heat pipe devices

4.2 Summary and Recommendations

This breakout session reviewed and discussed 10 contributed RFI responses in an open session. In addition to the RFI responses, more information was provided during the session by the workshop participants, session Chairs, and facilitators, all included in this report.

We separated the discussion into two primary areas: fundamental research and device and system research and development (R&D). Extensive support of both areas is needed for NASA to certify and then extensively use heat pipes in manned and unmanned missions. Outside of the detailed R&D directions that will be discussed later, the group came up with several recommendations.

1. Develop a multiuser, modular, heat pipe facility aboard the ISS that can handle fundamental thermal-fluid experiments and evaluate prototype heat pipe device designs.
2. Establish a working group to define a set of standard performance measures for heat pipes, akin to an American Society for Testing and Materials (ASTM) International standard set, so that different designs and configurations can be compared with one another.

3. Develop a plan for handling proprietary information and intellectual property that may result from work done on the ISS National Laboratory. (A review of the types of agreements used by other agencies such as the Department of Energy (DOE) or National Institutes of Health would be useful.)
4. Identify opportunities for interagency and international research collaborations and funding. Of particular interest are Air Force Office of Scientific Research (AFOSR), Office of Naval Research (ONR), Defense Advanced Research Projects Agency (DARPA), and National Science Foundation (NSF).
5. Develop a plan and schedule to fund and implement the above recommendations, including communicating effectively to the community about the types of research that are desired and will be funded. Allocate resources and provide access to required facilities.

Additional research areas proposed during the session include heat integration and process intensification, the use of machine learning and artificial intelligence (AI) techniques for assisting in model development, measurement of fundamental material properties associated with heat pipe design and operation, and the use of fluid mixtures at all temperature levels of anticipated operation.

4.3 Overarching Themes and Research Areas

Heat pipes are critical thermal management components of manned and unmanned space exploration missions because they contain no moving parts that need replacement or maintenance and because they can be made to operate efficiently in environments ranging from cryogenic fuel storage tanks to nuclear reactor systems. Unfortunately, the design of these systems still remain more of an art than a science so their full potential in NASA’s exploration plans remains unrealized. Based on RFI responses and discussions during the workshop sessions, six themes were identified and separated into fundamental and device areas.

What ties all these areas together is the critical need for a multiuser, modular, heat pipe facility aboard the ISS that can handle fundamental thermal-fluid experiments and evaluate prototype heat pipe device designs. This is a long-term goal since it will take several years to fund, design, and build the hardware. The facility on the ISS is required because as the constrained vapor bubble (CVB) experiments and related experiments by European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) have shown, unforeseen, emergent behaviors arise when the damping effect of gravity is eliminated and one works with a complete integrated system, rather than isolated components.

The facility should be able to work with virtually any heat pipe configuration and accommodate all manner of working fluids with the possible exceptions of very high and deep cryogenic temperature systems. Those could run outside the station. The facility should provide for visualization capabilities, measurements of power in and out of the device, measurements of internal device pressure(s), and as many measurements of temperature as possible along the device so that between the power and temperature measurements, researchers can model the systems and close an overall energy balance.

In the fundamental area, two major themes were identified:

- Interfacial and intermolecular phenomena
- Modeling, simulation, and performance prediction

In the device and system area, four themes were identified:

- Variable thermal links for lunar and Martian landers, rovers, and human habitats
- Freeze and thaw of long pipes with grooved condenser
- Long and three-dimensional (3D) OHPs
- Standardization of performance metrics and testing procedures

There are strong synergies among all these themes. The fundamental areas are designed to provide the background knowledge and tools required for device architects to design new systems while the performance of systems naturally serve as validation tools for the models and point to key knowledge gaps that must be closed by investigations at the fundamental level.

4.4 Fundamental Research Area

4.4.1 Interfacial and Intermolecular Phenomena

The area of interfacial and intermolecular phenomena comprises much of what is currently viewed as cutting-edge research in change-of-phase heat and mass transfer. It focuses on the interplay between fluid composition, surface chemistry and topography, the kinetics of phase change at the molecular level, and the overall device geometry including whether the system uses a wick or is wickless. It also touches on the use of external fields to modify interfacial phenomena and also on additive manufacturing techniques to realize complex geometries at the submicron level that may be used to develop novel wicked or wickless systems to enhance flow and phase change. In high-temperature systems, the interfacial reactions leading to corrosion also require further study. Some of the corrosion work is synergistic with DOE nuclear programs.

4.4.1.1 Key Research Areas

These areas represent a summary of what was submitted in RFIs and discussions that were held at the workshop. They are all interrelated, so prioritization is difficult. Most represent long-term goals since they would require the heat pipe facility to fully evaluate, though aspects can be started much sooner using existing facilities such as the Microgravity Science Glovebox (MSG) and Flow Boiling and Condensation Experiment (FBCE). The list below is in approximate order of priority.

- Surface modification—This includes both physical and chemical modification and is intimately tied to device geometry. Understanding how these three interact is important for phase management within devices, for optimizing fluid circulation, and for augmenting evaporation and condensation processes via enhanced nucleation. There are geometrical issues with the large-scale design of heat pipe systems, especially wickless systems, that could be coupled with surfaces that are being designed for plant water management and with past capillary flow surfaces. An understanding of how the two could be merged may make for improved designs for microgravity operation. Several RFIs addressed this topic as well as ideas that were presented at the workshop itself.
    - Knowledge gaps—Despite many years of research on surface modification and structure, the work is still largely Edisonian and there is virtually no theory on how to rationally design a surface outside of mimicking what we observe in nature. Therefore, fundamental research in the absence of gravity and in a gravitational environment is important if we are to better understand how to design devices from first principles that work in situations relevant to NASA’s exploration mission.

- Working fluids and phase-change kinetics—There are many fundamental questions concerning phase change that remain unknown. These range from microscopic aspects, like the influence of intermolecular forces between the vapor, liquid, and solid phases and how to reliably measure their strength, to the magnitude of accommodation coefficients, and the composition of the working fluid. The role of thermodynamics, intermolecular forces, and interfacial forces on the development and choice of rewetting fluids is a key area for research. Little detailed information is known about these systems apart from the number of phases that could exist within a given heat pipe. The role of mass transfer resistances in vapor and liquid mixtures and the effect of these resistances on the operation of phase-change devices is critical to their performance. This also includes the use of noncondensable gases (NCGs) to augment the conductance of the devices.
    - Knowledge gaps—How do we engineer device tunability by changing the composition of the working fluid to control wetting and rewetting and by introducing NCG into the systems? How do these fluids and fluid mixtures affect the kinetics and rate of phase change? If these fluids distill along the length of a heat pipe so that the fluid composition varies along its length, how do the resulting Marangoni forces affect overall device performance especially in microgravity?
- Fluid physics—Several fundamental fluid physics issues arose out of the OHP presentation and subsequent discussion. One concerned how large a diameter pipe could be used in microgravity. This relates to work on capillary bridges that NASA supported many years ago. The importance of this work was a problem encountered in these devices where an abundance of vapor forms altering the vapor slugs’ shape, which then penetrates through the liquid slugs to promote annular flow and kill performance. Some of this work has been done in the past looking at enhanced oil recovery and fracking operations, but these studies are in complex porous media and subject to 1g forces.
    - Knowledge gaps—Models for OHPs are very primitive. Simple experimental systems running in microgravity are required to develop theories about the critical conditions that lead to device failure. How these conditions are related to past work on capillary bridges and breakthrough needs to be determined.
- High- and low-temperature systems—In many respects, high-temperature and cryogenic systems are very different from moderate-temperature operation. The group thought this represented an opportunity to do two things. One is to develop moderate-temperature mimics to investigate some of the features of molten metal or molten salt systems. Ionic liquids might be used as molten salt substitutes to investigate fluid motion, fouling, and some corrosion issues. The second would be to team up with the materials group and run high-temperature heat pipe systems in the furnaces used for crystal growth, etc.
    - Knowledge gaps—There is not enough fundamental data on what happens as the systems freeze, how to restart them, how their ultra-low surface tensions affect performance, the effect of a potential three-phase flow on wicking structures, what geometries accommodate potential freezing best, and how the extreme environment of these molten salt or molten metal systems will affect device lifetime, container materials, and performance.
- Wicking versus wickless systems—Many capillary-driven devices operate using wicks, yet the design of wicks is still an open area of research. The field is only marginally more advanced than surface modification. Therefore, we need fundamental work in how to rationally design wicking structures and how that design affects evaporation and condensation, how it exacerbates or

alleviates choking if one starts to boil, and what the interactions are between the wick material and working fluid over longer time periods that lead to resistance or promotion of fouling.
    - Knowledge gaps—How do we rationally design wicking structures for different fluids? Are wicks needed at all in microgravity and how much gravity is required before wicks are required?
- Resonant enhancement—We discussed the idea of resonant enhancement of systems. This was brought out in one of the RFIs. The broader area is one of using external fields to help force the device operation and provide a knob to tweak its operation, not currently available for stabilizing and controlling heat pipe operation. This could be synergistic with electrohydrodynamic for boiling, but we also envisioned acoustic, optical, mechanical, or magnetic forces as well. Liquid hydrogen is paramagnetic so this latter ability may be useful for cryogenic heat pipe systems. Resonant forcing may also help with the onset of nucleate boiling (in LHPs, or thermosyphons on the ground) and perhaps could also be used to help with startup in alkali metal pool boilers.
    - Knowledge gaps—While there is information on electric field enhancements for boiling, there is limited information on how resonant enhancement would work in a heat pipe and how the resonance would be applied to enhance mixing in the system and drive enhanced heat transfer.
- Material properties—The use of external fields brought up the question of whether we know all the fundamental material properties required to implement any of these techniques. For example, we would have to know permittivities of the working fluids and container materials over wide ranges of frequency to understand their electrical response and to calculate the intermolecular force interactions between liquid vapor and solid.
    - Knowledge gaps—The data required does not now exist for all fluids and materials of relevance to heat pipes. This may be a good area to collaborate with National Institute of Standards and Technology and NSF since the data need not be collected in microgravity yet and is critically important for understanding the performance of microgravity devices.
- Fabrication methods and processes—Though this topic may seem to be a practical one, there are fundamental questions about how best to build devices. In particular, with the advent of additive manufacturing techniques, new geometries that were not possible before can be fabricated. This touches on system and device geometry as well as individual materials of construction that may have to avoid corrosion and fouling over time or provide a certain density of nucleation sites for evaporation and condensation. Since we can fabricate down to submicron dimensions, this also affects surface roughness and the structure of wicks.
    - Knowledge gaps—The basic questions here are: If I can build anything I can imagine, what should I build, how do I decide, and what principles must be followed? Do I maximize surface area or contact line length?
- Heat integration and process intensification—Manned exploration requires the development of highly integrated and coupled life support systems. Many of these systems that operate well in 1g cannot work in microgravity and require significant redesign. We discussed how heat pipe systems could be used in these kinds of scenarios by providing heat integration like that between heat-generating reactors and vacuum distillation units or that between processing plants on a lunar base that require heat integration. Also discussed were the integration of process units into smaller, more modular, and “intensified” systems like reactive distillation systems, or heat pipes that run coupled chemical reactions inside them or in reactors where they are embedded.

    - Knowledge gaps—On their own, heat pipe systems are designed to be open-loop stable devices. Integrating them into larger coupled systems means more experimentation is required so that they would be closed-loop stable. These new kinds of systems would also have to be extensively tested in both 1g and microgravity environments before they could be used on manned missions.

4.4.2 Modeling, Simulation, and Validation

Fundamental work on modeling and simulation techniques is required to advance heat pipe design and to qualify new systems for manned and unmanned missions. Two-phase and multiphase modeling tools like phase field, level set, and two-fluid systems can reproduce many features of what is observed experimentally but are still suspect quantitatively and so not entirely trustworthy for the detailed design of heat pipe devices. Moreover, good models are required to help guide experimentation and require excellent experimental facilities to help validate the models. The group discussed several aspects required to advance the state of the art.

4.4.2.1 Key Research Areas

These areas represent a summary of what was discussed during the workshop. There were no RFIs submitted in this area prior to the workshop but the discussion arose after the presentation on PHPs. Most represent long-term goals since they would require the heat pipe facility to provide the validating experimental results though aspects can be started much sooner through collaboration with NSF and use of existing ground-based data as well as NASA's Physical Sciences Informatics system. Some initial data can also be obtained from Air Force microgravity experiments on the X–37B and using existing facilities on the ISS such as the MSG. The list here is also approximately in order of decreasing priority.

- Continuum modeling—Work on two-phase flow models needs to continue. While there are some very good two-phase flow models developed for isothermal gas-liquid flows, the situation is quite a bit murkier when looking at vapor-liquid flows where phase-change heat transfer is occurring simultaneously. Some modeling in this area was recently funded during the DARPA Intrachip/Interchip Enhanced Cooling (ICECool) Fundamentals program, but these models served mostly to show how complicated such systems could be especially in complicated geometries. Transient models that could fundamentally describe the stochastic behavior of something like an OHP are barely adequate. Fundamental work on developing these models is required and that work cannot proceed without detailed experimentation both in 1g and microgravity. The experiments would be used for model validation and theory development.
    - Knowledge gaps—How do we design robust, efficient, two-fluid models that accurately and quantitatively represent the vapor-liquid interface in simple geometries such as in a wickless heat pipe or OHP? How do we extend those models to handle systems that contain wicks? Can these models be used to develop new performance measures? The coupling between phase change and overall system pressure and temperature distributions that allow one to reproduce the details of the vapor-liquid interface, such as those observed in the CVB experiments, is still elusive.
- Multiscale models—The holy grail of modeling would be to couple molecular dynamics simulations of phase change with continuum models for describing bulk fluid flow and heat transfer. Continuum models begin to break down severely near the contact line and at the vapor-liquid interface. The situation is complicated for a pure fluid where there is still a question about

the accommodation coefficient but becomes more complicated for fluid mixtures especially those like butanol-water where the phase diagram is quite complicated.

  - ○ Knowledge gaps—We do not fully understand how processes at the molecular level affect the macroscale, let alone the intimate coupling between evaporation and condensation, that are entangled over distances much longer than one would assume. How do we develop efficient, multiscale algorithms that couple molecular events at the contact line and vapor-liquid interface to continuum models describing fluid flow and overall thermal performance?

- Machine learning and AI—The group touched on the use of machine learning and AI to help develop correlations for heat pipe performance and also models that could be used to help control the devices or systems in which the devices are located. This was especially deemed useful in the realm of oscillating or pulsating heat pipes, where the training data required to develop a model could be obtained over a relatively short period of time. We discussed the ability to do combinatorial experiments on these devices, training the algorithms on that data to help identify the key variables that need further exploration so that we can perform enhanced experiments. Eventually these machine-learning tools would be used to develop better theoretical models that could be used to influence alternative device designs.
  - ○ Knowledge gaps—We do not necessarily know what or how much data would be required to develop a robust correlation. We do not know how many levels of deep learning would be required or whether the algorithms we train can predict performance outside the training set or only used to interpolate between points in the training set.

4.5 Device and System Research and Development

The highest priority for device and system R&D should be microgravity testing to qualify devices for lunar and Martian landers, rovers, and human habitats. Many of these devices also need to operate in gravity during transit to the Moon and Mars.

4.5.1 Variable Thermal Links for Lunar and Martian Landers, Rovers, and Human Habitats

Potential variable thermal links for the Moon and Mars need to also operate during transit. Devices that need to be validated in microgravity include

- Warm reservoir VCHPS
- LHPs with thermal control valves (TCVs)
- Phase-change material (PCM) heat sinks, potentially integrated with the LHPs or VCHPs

4.5.2 Freeze and Thaw of Long Pipes With Grooved Condensers

Freeze and thaw of long pipes needs to be validated in microgravity for the following applications:

- Aluminum and ammonia heat pipes to eliminate heaters
- Long sodium heat pipes for fission power
- Long water heat pipes for fission power

This is a lower priority than the variable thermal links, since the need is not as immediate. For the aluminum and ammonia CCHPs, the problem can be prevented by using electric heaters, with a minimal impact on satellites in orbit around the Earth.

The fission power systems are divided into two applications:

- The 10-kWe systems for the Moon and Mars—These systems are not anticipated to operate during transit. Validation of the thermosyphons can be accomplished during ground testing.
- The nuclear systems for use in spacecraft—Microgravity testing is needed for the heat pipes and the convertors. The timing of this will depend on the timing for using KiloPower (Refs. 1 and 2) in space.

4.5.3 Long and Three-Dimensional Pulsating Heat Pipes

Microgravity testing is also required for long and 3D OHPs. In contrast to the variable thermal links and long heat pipes freeze and thaw topics discussed previously, the 3D microgravity heat pipe testing is on a more fundamental level. The PHP models developed from ground-based testing need to be validated in microgravity.

4.5.4 Standardization of Performance Metrics and Testing Procedures

The community must get together to define a set of standard performance measures. At the device level, this could be something akin to a fin effectiveness or fin efficiency, while at the fundamental level we would be concerned with the fraction of input energy transported via evaporation and condensation versus conduction and radiation. This task would help us better organize the fundamental data, point toward key future experiments that are needed to fill knowledge and operational gaps, and enable standardized systems to be designed for exploration and used on different vehicles. At present, researchers report whatever metric puts their device in the best light.

4.6 Exploration Relevance

The fundamental areas discussed previously represent precompetitive research that would be used by industry to help develop optimized systems designed specifically for NASA exploration missions. This research would also be useful for DOD and commercial and consumer space applications by Blue Origin, SpaceX, and Virgin Galactic among others. High-temperature systems are also relevant to DOE nuclear reactor programs that are looking at using molten metal and molten salt heat pipes in modular reactors. They are currently funding some corrosion studies that include the effects of radiolytic decay.

The applied and device experimental needs would be focused on those engineering issues that must be overcome to develop practical and customized systems to further NASA exploration missions, such as lunar base power and environmental control, planetary exploration such as Europa or Titan missions, and for developing robust systems for long-duration manned and unmanned missions in microgravity that might make things like the large recent change in Galileo's orbit to avoid Jupiter's shadow or the periodic changes in the Geostationary Operational Environmental Satellite System (GOES)–17 satellite's operation unnecessary. These systems would also have terrestrial applications to the thermal management of avionics, directed energy weapons, high-capacity battery banks, and 3D and power electronics.

4.7 Recommended Partners

NASA internal—It would seem that a number of NASA centers would be involved in this effort including Glenn, Goddard Space Flight Center, and Jet Propulsion Laboratory for both manned missions and unmanned exploration. Other centers, including Kennedy Space Center, Johnson Space Center, and Langley Research Center, could also be involved in implementation on the ISS or in using heat pipes for advanced aviation.

Other U.S. agencies—The AFOSR and ONR have both funded efforts in the past on heat pipes of one form or another. The Air Force has interests in satellites and if not manned missions yet, the new space force will have to borrow and contribute to NASA's missions.

Other space agencies—The ESA and JAXA would be interested and have funded some efforts in the past. The Italian Space Agency has funded a wickless metal heat pipe that flew on the ISS and used water and pentane as working fluids.

Commercial—Space firms like SpaceX, Orbital, Virgin Galactic, Blue Origin, and Sierra Nevada could be likely partners.

4.8 Reduced Gravity Justification

Heat pipes in microgravity may exhibit behaviors that are generally masked by the effects of a large gravity vector. The issues are particularly acute as the diameter of the pipe increases and if the heat pipe is of a wickless design. As the magnitude of the gravity vector is reduced, buoyancy forces become negligible highlighting an increase in the importance of interfacial and capillary and Marangoni forces. These interfacial forces govern the thickness profile of the liquid films, the flow within those films, liquid bridging across the flow channel, freeze and thaw behavior, the phase distribution throughout the heat pipe, and the interfacial heat and mass transfer. Ultimately, the amount of heat that can be transported by the heat pipe and the robustness of this technique to potential instability mechanisms will be affected by the liquid replenishment to the heat acquisition section of the heat pipe system.

From the perspective of increasing fundamental insights into the interfacial behavior in these systems, a reduction in the gravitational force allows for the examination of surface tension driven flows and heat transfer in much larger systems that are amenable to the available diagnostic techniques. From an implementation standpoint, this knowledge provides much needed background information for designing larger diameter heat pipes, designing new wick structures, and investigating new configurations that would be optimized for microgravity or terrestrial conditions.

4.9 Facilities and Operational Needs

There are four different methods for microgravity (and reduced gravity) tests

1. Drop tower tests: ~5 s
2. Parabolic flight tests: ~30 s
3. Blue Origins: several minutes of microgravity
4. ISS: long as necessary

The different experiments discussed above need to be binned, using the least expensive test method that is suitable.

Three new equipment needs were identified:

- Variable gravity drop tower tests
- Passive Two-Phase Device Test Rig in the International Space Station (ISS)
- Test rigs on the outside of the ISS

The variable gravity drop tower tests will be required for simulating thermal systems that will be used on the Moon and Mars. The Passive Two-Phase Device Test Rig will be used for device tests that can safely be conducted in the interior of the ISS.

4.9.1 Variable Gravity Drop Tower Tests

Due to the increased interest in lunar and Martian landers and rovers, as well as manned installations on the Moon, NASA should consider how to modify the current drop towers to simulate lunar and Martian gravity.

4.9.2 Passive Two-Phase Device Test Rig for Testing Inside International Space Station

This test rig would be used to test VCHPs, LHPs, PHPs, PCM systems, and some pumped two-phase (P2P) components such as pumps and cold plates. The system would test with fluids that are safe for the astronauts, such as water, Freon$^{\text{TM}}$ (The Chemours Company), and ethanol. As a starting point, the concept, shown in Figure 1, will start with an earlier test rig, the Passive Heat Exchanger Rig (Refs. 3 and 4), which was also used for the Advanced Passive Thermal eXperiment (Ref. 5). The lower half is the support section, which supplies power, cooling fluids, etc. The upper half has removable, swappable lockers to test the different devices. Tests are run with minimal attention from the astronauts, who just need to swap the lockers in and out. The tests are run from the ground.

4.9.3 Tests Rigs Outside of International Space Station

These test rigs would be used to test devices with fluids that are unsafe inside the ISS:

- Aluminum and ammonia freeze and thaw testing with grooves and/or hybrid wicks
- Nuclear startup and shutdown testing
    - Test a KiloPower test setup with grooves and/or hybrid wicks
    - Long sodium heat pipe
    - Dynamic power convertor such as Stirling or Brayton
    - Long water heat pipes for heat rejection

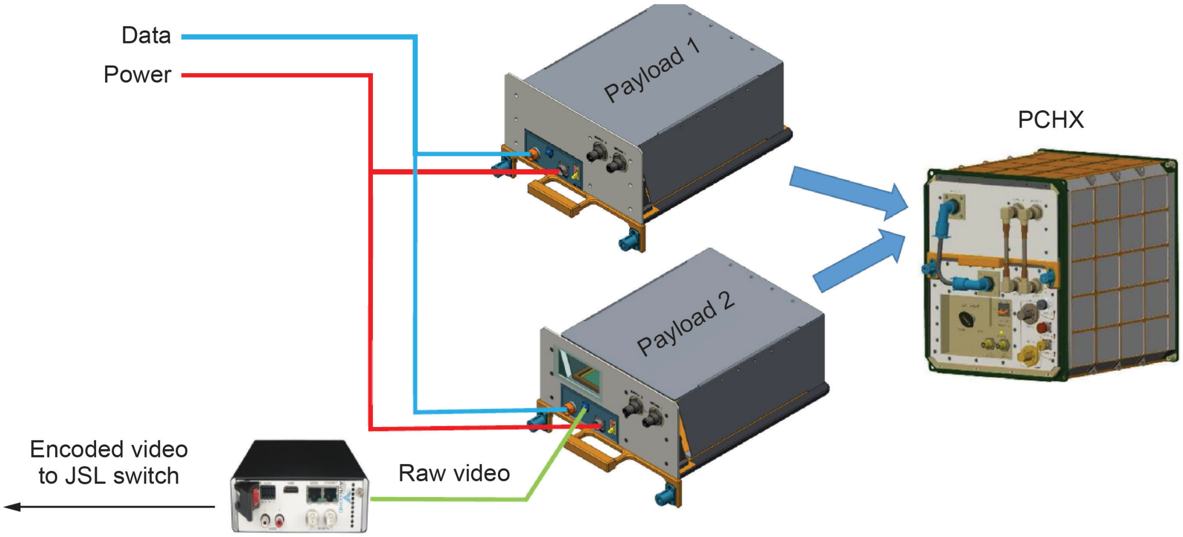


Figure 1.—Test rig is required to test passive (and active) two-phase devices on International Space Station. Joint station local area network (JSL). Phase-change heat exchanger (PCHX).

4.10 Requests for Information (RFIs)

4.10.1 Fundamental Research Requests for Information

4.10.1.1 Exploring NASA and National Science Foundation Collaboration Opportunities in Area of Heat Transfer and Fluid Dynamics.

The new program director for the Thermal Transport Processes program at the NSF is interested in exploring potential collaboration opportunities with NASA in fundamental heat transfer and fluid dynamics research that align with NASA's mission.

4.10.1.2 Wettability-Engineered Surfaces for Pumpless, Rapid Fluid Transport in Space

This RFI, described a new concept based on wettability-engineered surfaces acting as open-air platforms that can pumplessly and rapidly (speeds up to 0.5 m/s) propel liquids without the influence of gravity. Such speeds are not attainable in other capillary systems, and have, up to now, required channel flows driven by pumps. The approach has been demonstrated in the lab with experiments and theoretical analysis, and could open new horizons in spacecraft systems whose operation relies on fluid media. The method uses open microfluidic tracks that due to their shape, surface texture, and chemistry are capable of transporting a wide range of liquid volumes on a surface, overcoming viscous and other opposing forces (e.g., gravity) at length scales close to the capillary length of the working fluid. The approach can transport high flow rates in the form of liquid jets striking a solid surface, and deviated to a prescribed direction. The technology has been demonstrated with both aqueous and organic liquids (which feature low surface tension) in applications ranging from microfluidics to high-demand heat removal. Simple designs of wettability patterning have been used on various substrates (ranging from metals and polymers, to paper) to demonstrate complex liquid-handling tasks, for example, volume merging, splitting, and metered dispensing, some of which occur in 3D geometries where gravity opposed the fluid motion. The technology can also be used for liquid-fuel management in closed containers, as it can transport fluids along inner container walls without gravity assistance. Since the technology eliminates pumps and other control equipment in fluid-handling systems, adaptation of this approach may produce significant savings in space exploration.

The proposer envisions a two-stage program targeting the implementation of the technology in spacecraft applications. The work will start with ground experiments designed to validate and optimize the gravity-independent operation of select devices (vapor chambers for heat transfer, specialized container surfaces for pumpless fluid management, liquid-jet cooling systems, etc.) that rely on the technology and offer value to the space program. After the ground experiments, low-gravity platforms will be used to demonstrate the technology's effectiveness in zero-gravity environments in anticipation of longer-term performance-improving tests on the ISS.

4.10.1.3 Heat Transfer Enhancement Using Resonant Mixing

We propose to use resonance (either mechanical or acoustic) to create mixing in phase-change processes. This mixing will enhance heat transfer and can potentially delay or prevent dryout. This will have application to heat pipes in space and in micro heat exchangers on Earth where length scales are small. The research is technology readiness level (TRL) 1 to 2.

4.10.1.4 Bottom-Up Assembly of Functionalized Nanomaterials for Improved Control of Thermal and Capillary Properties of Solid and Fluid Interfaces

The key objectives of the proposed project are to employ and optimize a new fabrication method for thermodynamic control of the morphology and composition of self-assembled monolayers on nanoparticles, assembled, functionalized graphene on surfaces, and metamaterial assemblies of nanoparticles, to modulate the thermal and capillary properties of solid and liquid interfaces for improved heat transfer in applications involving plasmonic evaporation, cooling and heat transfer, and photocatalysis. In particular, water recovery applications and boiling and condensation applications seem particularly well-suited to this technology. It is a potential technological solution for several important problems in the very early stages of development with significant potential for dual-use application and further development beyond any initial applications.

4.10.1.5 Fundamental Study of Wickless Heat Pipes in Microgravity

Need a detailed experimental program to understand exactly how heat pipes behave and what are the fundamental limits to performance. Past work in microgravity has shown some unusual behaviors that should be re-explored with more sophisticated imaging and measurement techniques so that we can get at the root cause of the behavior and develop better theortical models.

4.10.2 Heat Pipe Devices

In addition to the fundamental research discussed previously, there is also a need for testing of heat pipe and P2P devices in microgravity. The RFI responses included the following devices:

- Heat pipes
- LHPs and CPLs
- PHPs, also known as OHPs
- Cryogenic heat transfer, possibly with flexible joints for zero-boiloff

Other devices that may require testing include:

- P2P devices and components (not discussed here, except for the test apparatus).
- Thermal storage (PCM) devices, which are often integrated with heat pipes (not discussed here).

The following device RFIs were submitted and discussed:

- Freeze and thaw of long pipes
    - Aluminum and ammonia heat pipes, to eliminate heaters
    - Long sodium heat pipes for fission power
    - Long water heat pipes for fission power
- Grooved and hybrid wicks
- Gas-loaded heat pipes
- 3D heat pipes
- Variable thermal links for lunar and Martian landers, rovers, and human habitats
    - Passive shutdown, without electrical power
- VCHPs and LHPs
- Cryogenic devices for zero-boiloff
- PHPs
    - 3D PHPs
    - Long PHPs

These experiments all take minutes to hours to start up, so they all must be tested on the ISS or other space platforms. The individual RFIs are discussed as follows.

4.10.3 Device Level Requests for Information

4.10.3.1 Freeze and Thaw of Aluminum and Ammonia Heat Pipes to Eliminate Heaters

Grooved aluminum CCHPs are a standard thermal control device, used in many NASA missions, as well as in military and commercial satellites. These CCHPs run the risk of bursting the pipe when the working fluid is frozen and later thawed. Ammonia, the most commonly used working fluid, freezes around –77.7 °C (194.3 K). Heaters and controllers are installed to prevent freezing, which can damage the heat pipes.

Reference 6 showed that these heaters could potentially be eliminated by using a gas-loaded heat pipe, see Figure 2. A gas-charged heat pipe (GCHP) is similar to a VCHP, since they both add NCG to the heat pipe.

Two differences occur as the power or heat sink temperature is reduced in a typical CCHP versus a GCHP. In a CCHP, the temperature drops in proportion to the power. In contrast, the GCHP provides a variable thermal link, since the NCG expands, and blocks a portion of the condenser. The other major difference occurs during freezing. In a CCHP, all of the fluid freezes in the condenser, forming a solid plug, which can damage the CCHP. When the liquid begins to freeze in the condenser section in a GCHP, the NCG will expand to fill the central core of the heat pipe, and ice will be formed only in the grooves located on the inner surface of the heat pipe in a controlled fashion. The ice will not bridge the diameter of the heat pipe, thus avoiding the risk of the pipe bursting during freeze and thaw cycles.

Figure 3 shows a successful startup of the gas-charged heat pipe in Figure 2. Twenty-seven freeze and thaw cycles were conducted under various conditions where the evaporator temperature ranged from 163 to 253 K and the condenser and reservoir temperatures ranged from 123 to 173 K. In all tests, the GCHP restarted without any problem with evaporator heat loads between 10 and 100 W. No performance degradation was noticed after 27 freeze and thaw cycles. The ability of the GCHP to sustain repeated freeze and thaw cycles was thus successfully demonstrated.

The GCHP must be validated in space, since it is possible that a liquid plug could form in zero-g, but not during ground testing; see Figure 4. During ground testing, gravity will force the liquid to form a puddle on the bottom of the heat pipe. It is generally accepted in the heat pipe community that freezing a liquid puddle will not damage a heat pipe, while freezing and thawing a slug that bridges the pipe diameter can damage the pipe. The ability of the GCHP to prevent liquid slug formation can only be demonstrated in space.

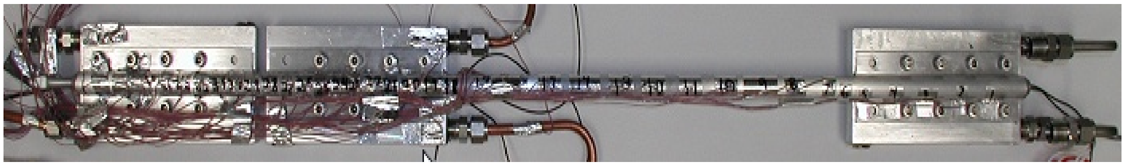


Figure 2.—Gas-charged heat pipes demonstrated freezing and thawing of aluminum and ammonia heat pipe condenser.

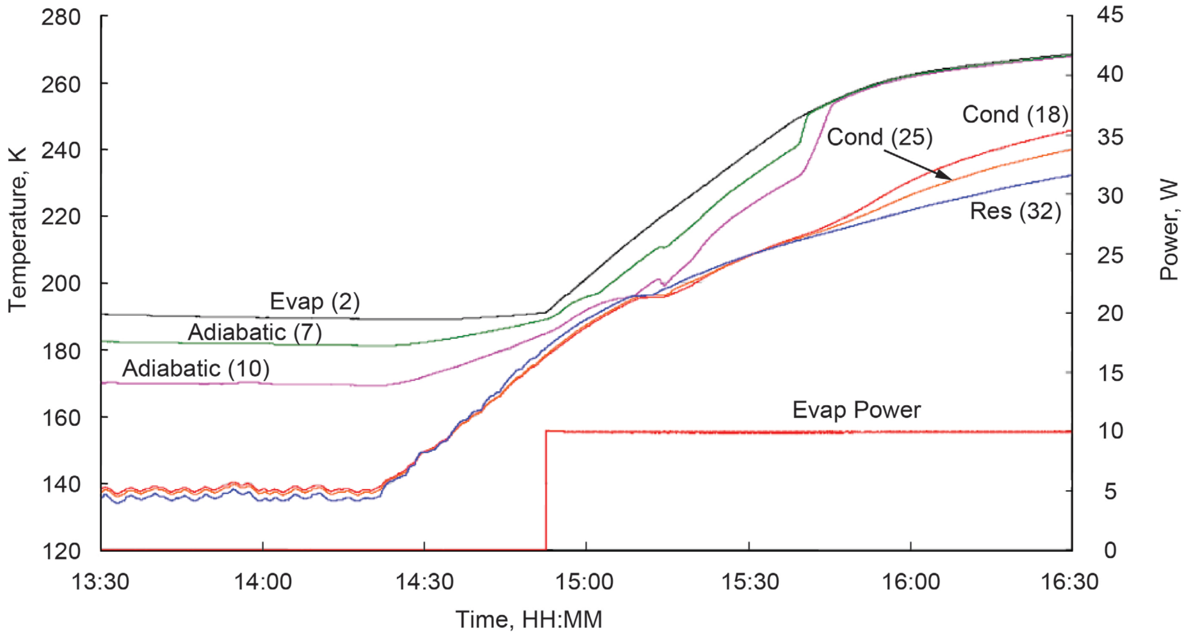


Figure 3.—Successful thawing of gas-loaded grooved aluminum and ammonia heat pipe, with condenser initially at 140 K, taken from Reference 6. Used with permission.

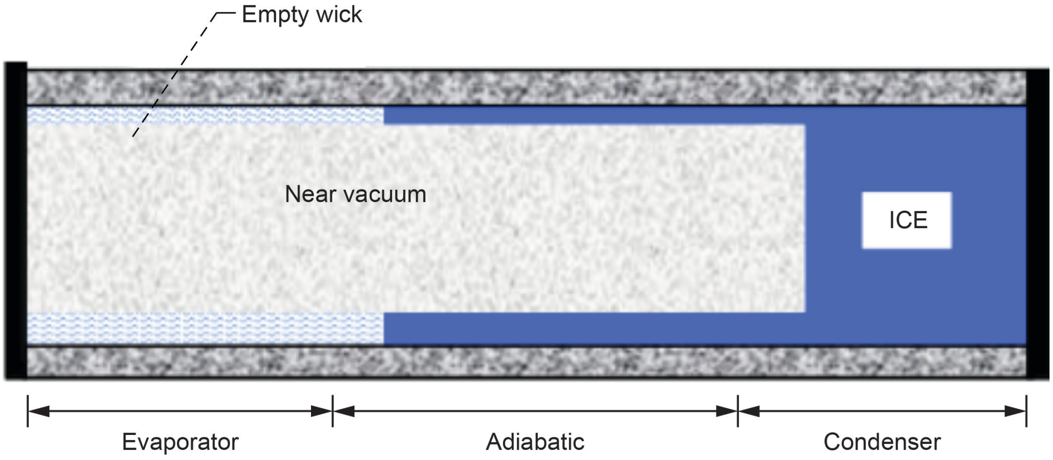


Figure 4.—Liquid plug forms at end of condenser in standard constant conductance heat pipe and could damage it. Microgravity tests are required to demonstrate that this will not be a problem with gas-charged heat pipe.

4.10.3.2 Three-Dimensional Constant Conductance Heat Pipe Validation for NASA

Because of their grooves, CCHPs can transport power over long distances in space. However, the wide grooves limit the adverse elevation (evaporator above condenser) that CCHPs can be tested. The standard is 0.1 in. (2.5 mm), where variations of 0.01 in. (0.25 mm) can significantly affect the measured maximum power.

Initially, all CCHPs were planar or two dimensional (2D), allowing them to be ground tested, see Figure 5 (right). Over the past 10 years, some commercial and military satellites used 3D CCHPs, see Figure 5 (left). They were initially validated by fabricating and ground testing 2D CCHPs with the exact same bends, but this is no longer required.

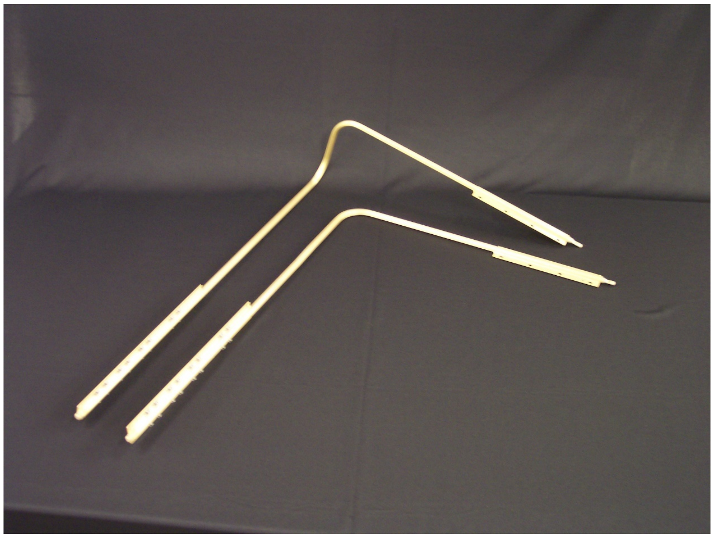


Figure 5.—Constant conductance heat pipes can be either two dimensional (right) or three dimensional (left).

NASA's thermal designs still only contain 2D CCHPs. While this more conservative approach makes sense for large missions, NASA should explore using 3D CCHPs in CubeSats and SmallSats. This may require microgravity testing to validate the 3D CCHPs. Note that this is a lower priority than the other devices discussed here, since the 2D heat pipes can be substituted.

4.10.3.3 Variable Thermal Links for Lunar and Martian Landers, Rovers, and Human Habitats

One of NASA's near-term goals is to send landers and rovers to locations near the lunar south pole. Spacecraft thermal designers are faced with the unprecedented challenge to survive extended excursions on the cold and frigid environment of the lunar night, potentially using only resistive heating. Lunar landers and rovers must be able to survive the 14-day-long lunar night. For solar-powered systems, minimizing electrical power usage at night is extremely important since 1 W of power over the entire night requires 5 kg of solar cells, batteries, etc.

Variable thermal links are required for lunar thermal control architectures. During the long lunar day, the thermal management system must be capable of removing the waste heat from the electronics, batteries, and instruments and ensuring that they do not get too warm. During the lunar night (or when traveling in a dark crater), the thermal management system must minimize the heat lost to the environment to minimize the amount of power required. Ideally, the variable thermal link will adjust passively, so that no electrical power must be supplied.

In addition, note the landers and rovers will need to reject heat during transit to the Moon. For this reason, they must be validated in microgravity. The thermal devices that need to be validated include:

- LHPs with TCVs
- Warm-reservoir VCHPs
- PCM thermal storage modules

4.10.3.4 Loop Heat Pipes With Thermal Control Valves

The LHPs are a standard thermal control device used in many microgravity applications. Similarly, TCVs are at TRL 9, having been used in Martian Rovers. When the TCV gets cold enough (cold condenser), the LHP stops operating (the condenser gets very cold, while the evaporator remains warm), and heat is lost at a very slow rate (Figure 6 and Figure 7).

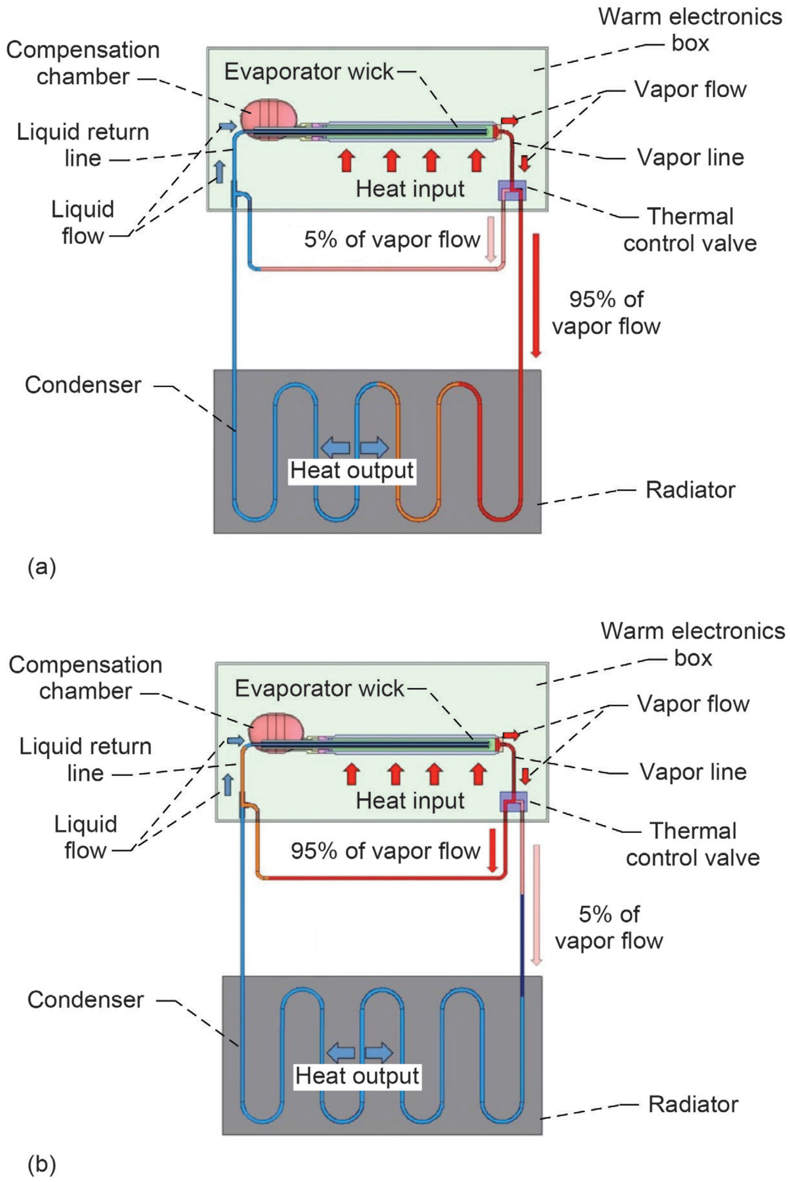


Figure 6.—Loop heat pipe with thermal control valve (TCV). (a) During lunar day, TCV is warm, and most vapor flows through radiator. Flow rates of 5 and 95 percent are representative. (b) As temperature drops, TCV shifts position. Most flow short-circuits radiator, flowing directly back into compensation chamber, minimizing heat loss. Used with permission.

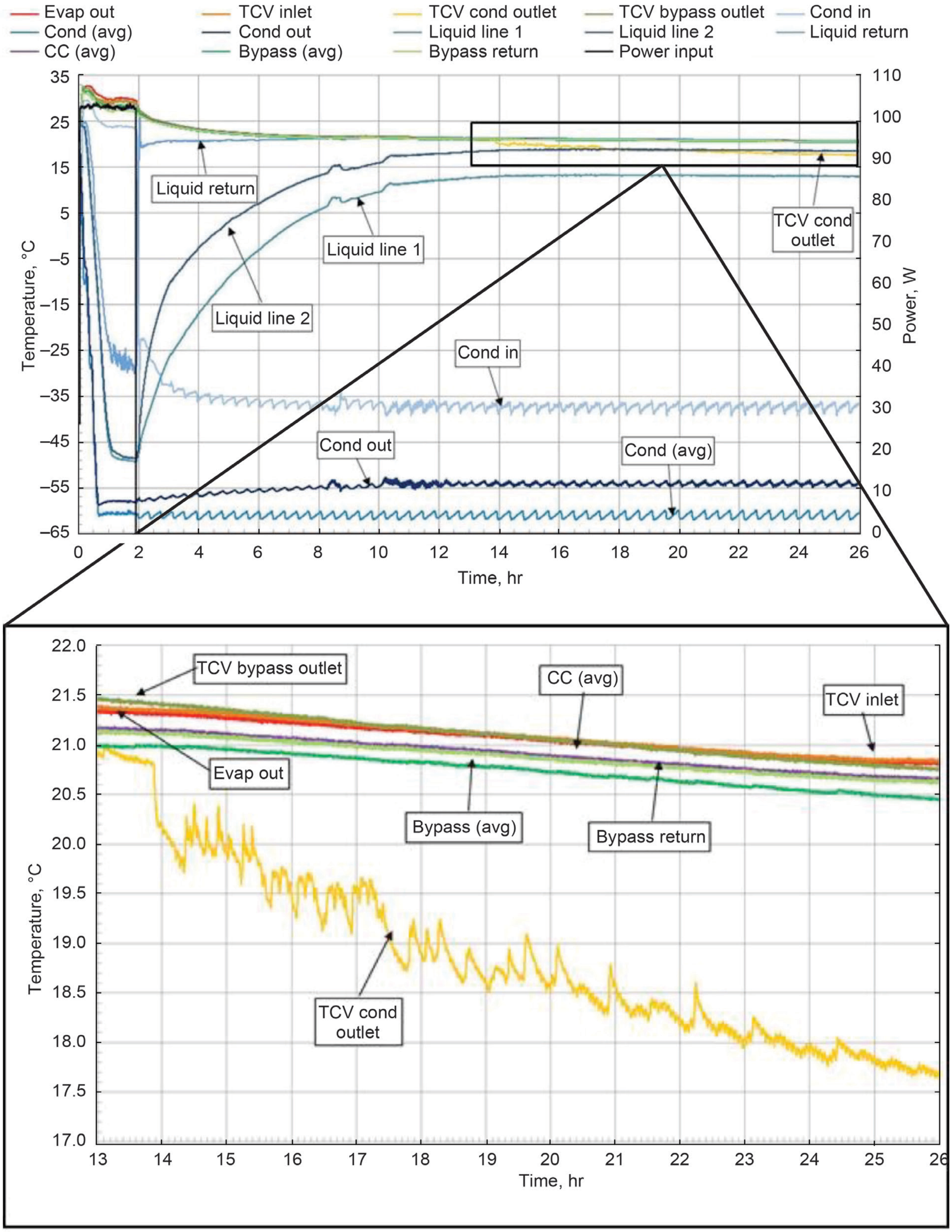


Figure 7.—Loop heat pipe (LHP) with thermal control valve (TCV). Used with permission.

The two devices have been validated together during ground testing (Ref. 7), but have not been tested together in microgravity. This is required before using the LHP with TCV in microgravity, and on the Moon.

4.10.3.5 Warm-Reservoir Variable Conductance Heat Pipes

In a conventional VCHP, the cold-biased NCG reservoir is located at the condenser end of the VCHP (Refs. 8 and 9). The cold-biased reservoir is electrically heated to maintain the desired temperature, typically requiring several Watts of electric power. This is a good solution for a satellite, when the eclipse times and high electrical heating times are short.

For a lunar lander or rover, the reservoir electrical heater power is eliminated by using a warm-reservoir ammonia VCHP, as shown in Figure 8, where the reservoir is adjacent to the evaporator. As shown in Figure 9, the evaporator remained warm while the condenser temperature was lowered to roughly –200 °C. The condenser was successfully frozen while the evaporator remained warm. Startup was then demonstrated.

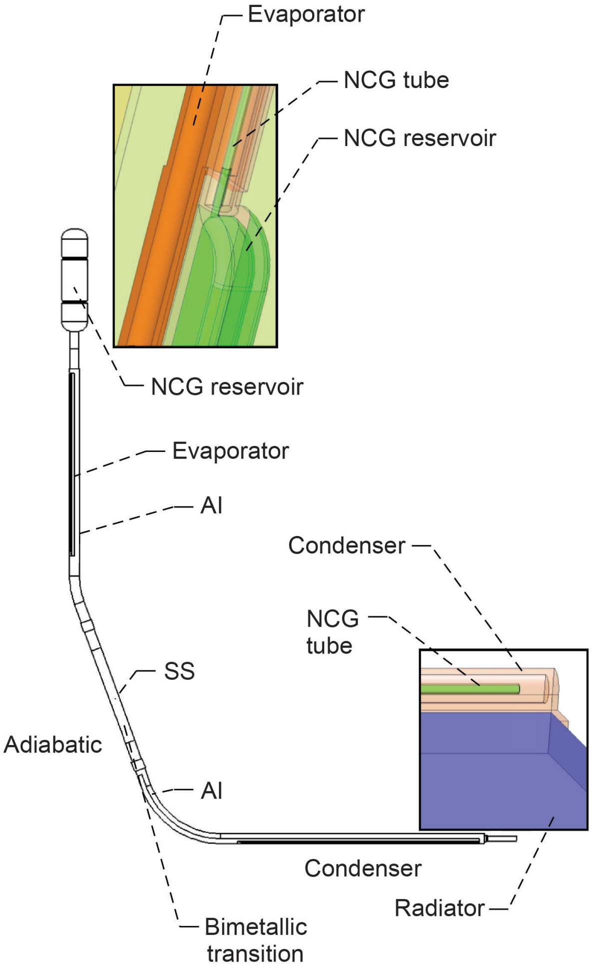


Figure 8.—In warm-reservoir variable conductance heat pipe, noncondensable gas (NCG) reservoir is located adjacent to evaporator, in warm region of lander or rover. Reservoir is connected to condenser with tube running through heat pipe. Aluminum (Al). Stainless steel (SS).

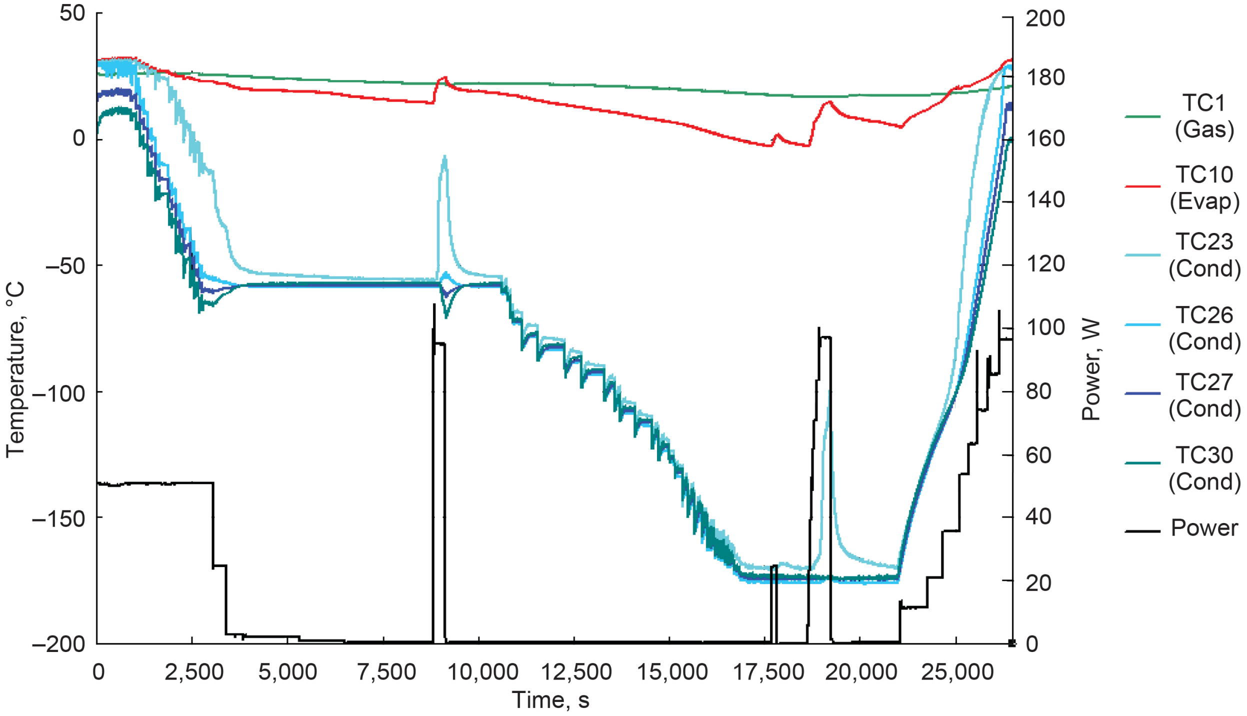


Figure 9.—Warm reservoir variable conductance heat pipe freeze and thaw results. Phase-Change Material Thermal Storage Modules.

In the 2015 NASA Roadmap, TA 14 (Ref. 10), NASA says: “Two-phase devices [heat pipes] are often used to accomplish heat transport. Heat rejection is accomplished through deployable or body-mounted radiators that essentially have a fixed emissivity and view to the space environment. The combined SOA [state of the art] results in more massive, less reliable systems due to the complexity of the dual-loop system and the need to reject heat at maximum mission heat loads and hottest thermal environments.”

NASA is exploring the addition of thermal storage to significantly reduce the required radiator size, mass, and cost (Ref. 4). “The lunar orbital environment presents very unique challenges for the thermal control system. Figure 10 shows the spatial variation of the lunar surface temperature. The hottest portion of the lunar surface corresponds to the point directly aligned with the sun (subsolar point). In the figure, the maximum surface temperature is approximately 400 K while the minimum temperature is less than 100 K on the dark side. The extreme surface variation results in a large swing in radiator sink temperatures while the vehicle is operating in low lunar orbit (LLO). The large sink temperature variations are problematic because it is impractical (sometimes even impossible) to use a radiator as the sole means of heat rejection during LLO if the vehicle’s radiators have a large infrared incident load from the lunar surface. The sink temperature corresponding to the location immediately above the subsolar point exceeds the setpoint temperature of the thermal control system.”

One method to reduce the required radiator size is to add PCM thermal storage. By absorbing the heat when the heat sink temperature is too high, the heat is released when the sink conditions are more favorable. The PCM thermal storage is also beneficial in some satellite applications, such as high-power radio transmissions to Earth, that occur relatively briefly during the orbit. One reason is that the available power may be limited (i.e., stored in batteries). Another reason is if the transmission occurs only when the spacecraft is located above a certain location. In particular, SmallSats and CubeSats may require PCM thermal storage, since they have a relatively low heat capacity.

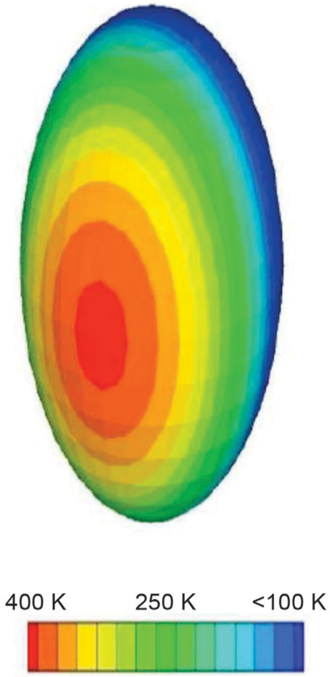


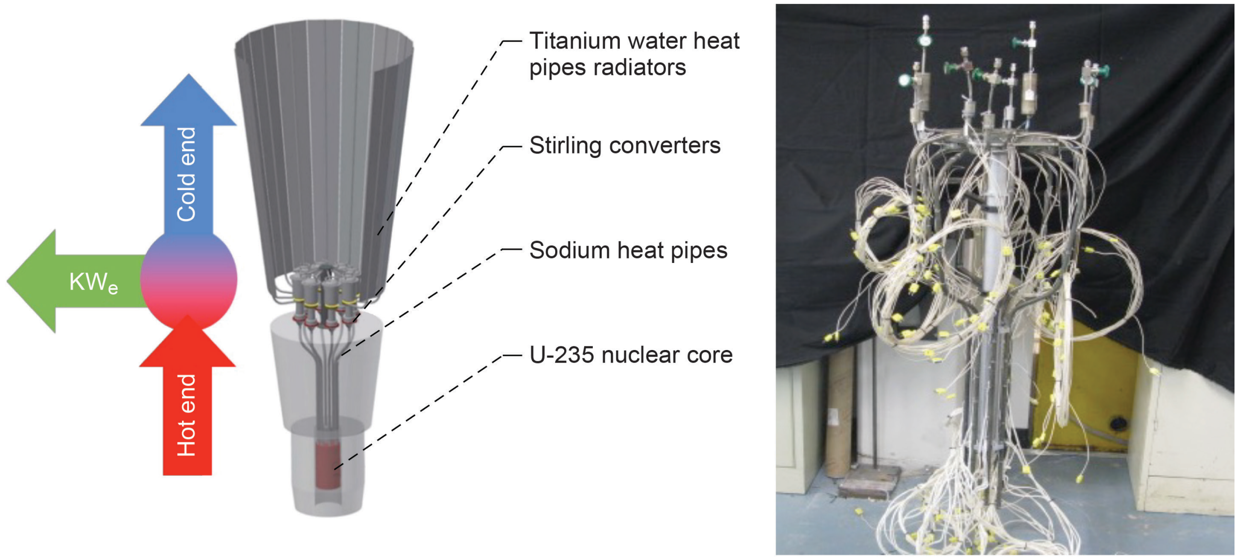
Figure 10.—Spatial distribution of lunar surface temperature taken from Reference 11. Used with permission.

NASA has conducted some PCM heat sink experiments on the ISS using the Passive Heat Exchanger Rig (Ref. 3). However, we believe that more may be needed in the future. Wax PCMs generally have a very low thermal conductivity, on the order of 1 W/mK. To enhance heat transfer, fins and/or heat pipes are normally required that extend into the PCM. One problem that must be handled is void location in the PCM as it freezes. The PCM liquid density is higher than the solid density, so voids form as the PCM is frozen (Ref. 12). On Earth, gravity can be relied on to keep the liquid on the bottom of the heat sink. However, the location of the void must be controlled in microgravity. Additional microgravity experiments on freezing and thawing of PCM in heat sinks must be conducted.

4.10.3.6 Alkali Metal and Water Heat Pipes for Nuclear Reactors in Microgravity, Moon, and Mars

The NASA Technology Roadmap, TA 3.1.5 (Ref. 13), Fission says that “Applications of fission with thermoelectric or Stirling heat engine conversion at an ~1 kWe power level support NASA’s science missions, while small 1 to 10 kW fission systems and larger 10 to 100 kWe fission systems are needed for Mars surface missions. Also, multi-MWe systems are promising options for advanced propulsion vehicles to support human exploration missions.”

The current NASA reactor design, KiloPower, is designed to produce from 1 to 10 kWe for space, lunar, and Martian missions (Refs. 1 and 2). As seen in Figure 11, KiloPower reactors designed for use in microgravity use long, hybrid sodium heat pipes to deliver the heat from the reactor to the power convertors (Ref. 14). These heat pipes have a screen or sintered evaporator wick and a grooved adiabatic condenser wick. Similarly, the waste heat is removed by a series of hybrid-wick and water heat pipes (Ref. 15). Short alkali metal and water heat pipes with screen or sintered wicks have both operated in microgravity. However, note that the KiloPower heat pipes are significantly different than these earlier heat pipes, since they can be several meters long, as opposed to 25 cm long for the earlier microgravity screen or sintered heat pipes.



(a) (b)

Figure 11.—KiloPower reactor. (a) Reactor uses sodium heat pipes (or thermosyphons on Moon and Mars) to deliver heat from reactor to convertors. Waste heat is then rejected by titanium and water heat pipe radiator, or pumped loop and heat pipe radiator. (b) Sodium thermosyphons developed for KiloPower reactor (Ref. 2).

One aspect of long alkali metal and water heat pipe designs that must be validated in microgravity is startup and shutdown from a frozen state (Ref. 16). When the condenser is much colder than the evaporator during startup, it is possible for all of the working fluid to freeze in the adiabatic and condenser sections and prevent the heat pipe from operating. The addition of NCG has been shown to allow startup in normal gravity, but needs to be demonstrated during microgravity.

Second, preventing damage from water during freeze and thaw must be demonstrated in microgravity, by preventing the water from bridging the vapor space. This is relatively easy to do by controlling the water inventory in short screened or sintered heat pipes. Wick design to prevent damage in long, grooved water heat pipes have been demonstrated on Earth, but needs to be demonstrated in microgravity.

4.10.3.7 Cryogenic Devices for Zero-Boiloff

Cryocoolers can be used to cool zero-boiloff tanks containing cryogenic liquids such as liquid nitrogen, oxygen, and possibly hydrogen. This allows the tanks to remain cold for long periods without venting liquid. An alternate is to have a deep space radiator in thermal communication with the tank. In either case, NASA needs cryogenic two-phase heat transfer devices to transfer heat from the tank to the cryocooler or radiator. A thermal aspect that needs to be addressed is the relatively large evaporator area that may be needed. The CCHPs and conventional LHPs have relatively small evaporator areas.

The option that could be used include:

- Cryogenic CCHPs, potentially with OHPs to collect the heat
- A cryogenic LHP with a large-area evaporator; see Figure 12

Both systems would require microgravity thermal testing to validate them.

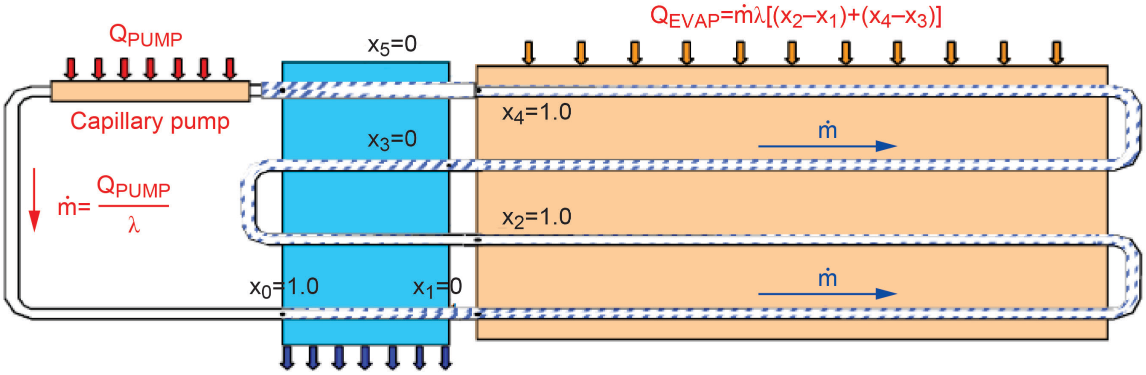


Figure 12.—Cryogenic loop heat pipe design with large-area evaporator (Ref. 17).

4.10.3.8 Microgravity and 1g Testing of Meter-Scale Oscillating Heat Pipes With Out-of-Plane Bends

There is a need for more efficient, passive heat acquisition, transport and spreading for space applications, including human exploration missions, lunar and planetary outposts, and commercial spacecraft. Such applications often require heat transport over meter-scale distances with 3D features such as multiple tight radius bends. With this, heat generated within a vehicle or habitat can be carried to an external surface or sink for rejection without needing to be coplanar. The OHPs are gaining acceptance in the aerospace and defense industries. They can transport significant heat loads over areas or lengths greater than 1 m with low temperature drop and can include multiple out-of-plane bends and 3D features thus, potentially, meeting this future need.

Reference 18 presented results from a study (NASA Phase I SBIR Contract 80NSSC18P2182) in which a 1.12-m-long OHP transported 600 W with an overall conductance of 200 W/°C. Reference 19 presented 1g test results for a 1.07-m OHP with six tight out-of-plane bends showing good thermal performance and little thermal effect of adding such bends. Applying OHPs to critical missions requires not only empirical data but also predictability of their operational limits. Reference 20 presented OHP limits substantiated by ground tests and supported by the Advanced Structural Embedded Thermal Spreader-II flight experiment aboard an X–37B, which has more than 19 months of successful microgravity operation. Three OHPs in this experiment are flat and relatively small, 50.8 by 152.4 mm, and well suited for many electronics cooling applications.

Critical questions remain regarding how OHP devices with relatively long and complex 3D shapes behave on ground relative to microgravity environments. The tests needed here will further corroborate this model so that OHPs designed for lunar or planetary application will have a predictable thermal resistance including gravity and bend effects. A solid foundation for scaling OHP performance with gravity loading and bending is critical for future space and planetary missions. One possible application is using solidified regolith as a stable heat sink. Such a solidified mass, buried under the surface regolith, would be a useful insulated heat sink and source if heat could be brought down to it when the block becomes colder than the environment on the surface when the lunar day sets in. During lunar night, it could be a useful source of heat for outposts or possibly for power generation. Conventional heat pipes have difficulty transporting heat downward but OHPs would be well suited for this need. This is one notional OHP application, but there are many other possible uses. Long OHPs with 3D geometry are likely to have an important role to play in future human spaceflight missions; better corroboration is needed for the effects of 3D bends and gravity on their operation.

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Appendix A.—Acronyms

2D	two dimensional
3D	three dimensional
3dp	three-dimensional printed
AFOSR	Air Force Office of Scientific Research
AI	artificial intelligence
ASTM	American Society for Testing and Materials
Bo	Bond number
BXF	Boiling Experiment Facility
CCHP	constant conductance heat pipe
CHF	critical heat flux
CPL	capillary pumped loops
CVB	constrained vapor bubble
DAQ	data acquisition
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
EHD	electrohydrodynamic
ESA	European Space Agency
FBCE	Flow Boiling and Condensation Experiment
FIR	Fluid Integrated Rack
Fr	Froude number
GCHP	gas-charged heat pipe
GM	General Motors
GOES	Geostationary Operational Environmental Satellite system
HVAC	heating, ventilation, and air conditioning
ISS	International Space Station
Ja	Jakob number
JAXA	Japan Aerospace Exploration Agency
LHP	loop heat pipes
LLO	low lunar orbit
MSG	Microgravity Science Glovebox

NCG	noncondensable gas
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
OHP	oscillating heat pipes
ONR	Office of Naval Research
P2P	pumped two-phase
PBRE	Packed Bed Reactor Experiment
PCM	phase-change material
PG&E	Pacific Gas and Electric Company
PHP	pulsating heat pipes
R&D	research and development
RFI	Request for Information
SBIR	Small Business Innovation Research
SLPSRA	Space Life and Physical Sciences Research and Application
SOA	state-of-the-art
TCV	thermal control valve
TRL	technology readiness level
VCHP	variable conductance heat pipes
We	Weber number
ZBOT	Zero Boil-Off Tank Experiment

Appendix B.—Workshop Registrants

The registrants' names, affiliations, and sessions attended are found in Table B.1.

TABLE B.1.—WORKSHOP REGISTRANTS

First Name	Last Name	Company	Session
Iwan	Alexander	University of Alabama at Birmingham	Boiling & Condensation
Jeffrey	Allen	Michigan Technological University	Boiling & Condensation
Jonathan	Allison	Air Force Research Laboratory	Heat Pipes
Bill	Anderson	Advanced Cooling Technologies, Inc.	Heat Pipes
Hitoshi	Asano	Kobe University	Boiling & Condensation
Virginia	Ayres	Michigan State University	Boiling & Condensation
Vemuri	Balakotaiah	University of Houston	Water Recovery
Ramaswamy	Balasubramaniam	Case Western Reserve University and NASA Glenn Research Center	Water Recovery
Debjyoti	Banerjee	Texas A&M University	Boiling & Condensation
Raymond	Beach	NASA Glenn Research Center	Boiling & Condensation
Kishan	Bellur	Michigan Technological University	Boiling & Condensation
Alfredo	Bencomo	Open Source Robotics Foundation	Boiling & Condensation
Greg	Bewley	Cornell University	Boiling & Condensation
Sushil	Bhavnani	Auburn University	Boiling & Condensation
Sajjad	Bigham	Michigan Tech University	Boiling & Condensation
James	Bird	Boston University	Boiling & Condensation
Daphne	Blumin	University of Michigan	Boiling & Condensation
Huseyin	Bostanci	University of North Texas	Boiling & Condensation
Lydia	Bourouiba	Massachusetts Institute of Technology	Water Recovery
Thomas	Boziuk	Georgia Institute of Technology	Boiling & Condensation
Leon	Brendel	Purdue University	Boiling & Condensation
Claudette	Brimmer	--	Water Recovery
Nevin	Brosius	University of Florida	Boiling & Condensation
Paul	Burke	Texas A&M University Aerospace Engineering Department	Boiling & Condensation
Karl	Cardin	Portland State University	-------------------------------
Van	Carey	University of California at Berkeley	Boiling & Condensation
Layne	Carter	NASA Marshall Space Flight Center	Water Recovery
Leonardo	Chamorro	University of Illinois at Urbana-Champaign	Heat Pipes
David	Chao	NASA Glenn Research Center	Heat Pipes
Zhengdong	Cheng	Texas A&M University	Water Recovery
Francis	Chiaramonte	NASA Headquarters	Boiling & Condensation
Ahsan	Choudhuri	The University of Texas at El Paso	Boiling & Condensation
Jacob	Chung	University of Florida	Boiling & Condensation
Giancarlo	Corti	Miami University	Water Recovery

TABLE B.1.—Continued.

First Name	Last Name	Company	Session
Kirt	Costello	NASA Johnson Space Center	Boiling & Condensation
Kevin	Crosby	Carthage College	Boiling & Condensation
Steven	Darges	Purdue University	Boiling & Condensation
Sam	Darr	The Aerospace Corporation	Boiling & Condensation
Suprem	Das	Kansas State University	Boiling & Condensation
Jesse	Defiebre	NASA Glenn Research Center	------------------------------
Jeffrey	Derby	University of Minnesota	Boiling & Condensation
Zachary	Deziel	NASA Wallops Flight Facility	Boiling & Condensation
Navdeep	Dhillon	California State University Long Beach	Boiling & Condensation
Vijay	Dhir	University of California, Los Angeles	Boiling & Condensation
Jeffrey	Didion	NASA Goddard Space Flight Center	Heat Pipes
John	Donehoo	The Space Team	Water Recovery
Bruce	Drolen	ThermAvant Technologies, LLC	Heat Pipes
Lian	Duan	The Ohio State University	Heat Pipes
Walter	Duval	NASA Glenn Research Center	Water Recovery
Ryan	Edwards	NASA Glenn Research Center	Heat Pipes
Dwight	Epps	Katsujinken Foundation	Boiling & Condensation
Amanda	Evans	Los Alamos National Laboratory	Water Recovery
Ali	Fares	Prairie View A&M University	------------------------------
Muhammad	Farooq	Embry-Riddle Aeronautical University	Heat Pipes
Andrei	Fedorov	Georgia Tech	------------------------------
James	Ferri	Virginia Commonwealth University	Water Recovery
Brian	Finley	ZIN Technologies Inc	Boiling & Condensation
Haider	Flayyih	www.evolvingspecies.com	Water Recovery
Ben	Furst	NASA Jet Propulsion Laboratory	Heat Pipes
Suleyman	Gokoglu	NASA Glenn Research Center	Water Recovery
Natasha	Gorski	Interphase Materials	Boiling & Condensation
John	Graf	NASA Johnson Space Center	------------------------------
José	Graña-Otero	University of Kentucky	Boiling & Condensation
Robert D.	Green	NASA Glenn Research Center	Water Recovery
Amelia	Greig	University of Texas at El Paso	Boiling & Condensation
DeVon	Griffin	NASA Headquarters	Boiling & Condensation
Roman	Grigoriev	Georgia Institute of Technology	Heat Pipes
Carlos	Grodsinsky	ZIN Technologies	Boiling & Condensation
Nail	Gumerov	University of Maryland	Boiling & Condensation
Monica	Guzik	NASA Glenn Research Center	Boiling & Condensation
Mustafa	Hadj-Nacer	University of Nevada, Reno	Boiling & Condensation
Nancy	Hall	NASA Glenn Research Center	Boiling & Condensation

TABLE B.1.—Continued.

First Name	Last Name	Company	Session
Caleb	Hammer	University of Maryland	Boiling & Condensation
Hans	Hansen	NASA Glenn Research Center	Boiling & Condensation
Jason	Hartwig	NASA Glenn Research Center	Boiling & Condensation
Mojib	Hasan	NASA Glenn Research Center	Boiling & Condensation
Yassin	HASSAN	Texas A&M University	Boiling & Condensation
Tyler	Hatch	NASA Glenn Research Center	Water Recovery
Dan	Hauser	NASA Glenn Research Center	------------------------------
Uday	Hegde	Case Western Reserve University	Water Recovery
Hui	Hu	Iowa State University	Boiling & Condensation
Melany	Hunt	California Institute of Technology	Water Recovery
Gisuk	Hwang	Wichita State University	------------------------------
Sonya	Hylton	Case Western Reserve University	Boiling & Condensation
Carlo Saverio	Iorio	Université Libre de Bruxelles	Heat Pipes
Andrew	Jackson	Texas Tech University	Water Recovery
Don	Jaekle	PMD Technology	------------------------------
Darrell	Jan	NASA Ames Research Center	Water Recovery
Wei	Ji	Rensselaer Polytechnic Institute	Boiling & Condensation
Mike	Johanson	ZIN Technologies	Heat Pipes
Wesley	Johnson	NASA Glenn Research Center	Boiling & Condensation
Ron	Joslin	National Science Foundation	Boiling & Condensation
Sunghwan	Jung	Cornell University	Water Recovery
Olga	Kartuzova	Case Western Reserve University	Boiling & Condensation
Mohammad	Kassemi	Case Western Reserve University	Boiling & Condensation
Massoud	Kaviany	University of Michigan	Boiling & Condensation
Chirag	Kharangate	Case Western Reserve University	Boiling & Condensation
Prashant	Khare	University of Cincinnati	Boiling & Condensation
Boris	Khusid	New Jersey Institute of Technology	Boiling & Condensation
Jungho	Kim	University of Maryland	Boiling & Condensation
Sunwoo	Kim	University of Alaska Fairbanks	Boiling & Condensation
Lou	Kondic	New Jersey Institute of Technology	Boiling & Condensation
Cable	Kurwitz	Texas A&M University	Water Recovery
Like	Li	Mississippi State University	Heat Pipes
Zhi	Liang	California State University, Fresno	Heat Pipes
Paolo	Luzzatto-Fegiz	University of California, Santa Barbara	Boiling & Condensation
Daniele	Mangini	HE Space for ESA	Heat Pipes
Bob	Manning	Keystone Engineering Company	Boiling & Condensation
Qussai	Marashdeh	Tech4Imaging LLC	Boiling & Condensation
Jeff	Marchetta	University of Memphis	Boiling & Condensation

TABLE B.1.—Continued.

First Name	Last Name	Company	Session
Shalabh	Maroo	Syracuse University	Heat Pipes
Robert	McMillin	Virginia Commonwealth University	Water Recovery
Ezra	McNichols	NASA Glenn Research Center	Heat Pipes
John	McQuillen	NASA Glenn Research Center	Heat Pipes
Dino	Megaridis	University of Illinois at Chicago	Boiling & Condensation
Eckart	Meiburg	University of California, Santa Barbara	Boiling & Condensation
Michael	Meyer	NASA Langley Research Center	Boiling & Condensation
Ian	Miller	Bastion	Water Recovery
Arman	Mirhashemi	NASA Glenn Research Center	Heat Pipes
Sam	Moffatt	Sierra Nevada Corporation	Boiling & Condensation
Saeed	Moghaddam	University of Florida	Boiling & Condensation
Michael	Moldover	National Institute of Standards and Technology	Boiling & Condensation
Kasra	Momeni	Louisiana Tech University	Boiling & Condensation
Brian	Motil	NASA Glenn Research Center	Water Recovery
Issam	Mudawar	Purdue University	Boiling & Condensation
Henry	Nahra	NASA Glenn Research Center	Boiling & Condensation
Ranga	Narayanan	University of Florida	Boiling & Condensation
Shankar	Narayanan	Rensselaer Polytechnic Institute	Boiling & Condensation
Vinod	Narayanan	University of California, Davis	Boiling & Condensation
Chanwoo	Park	University of Missouri	Boiling & Condensation
Martin	Patton	Emmo Instruments	Boiling & Condensation
Howard	Pearlman	Advanced Cooling Technologies, Inc.	Boiling & Condensation
Justin	Pesich	NASA Glenn Research Center	Boiling & Condensation
Christopher	Pestak	Universities Space Research Association	Boiling & Condensation
Michael	Peterson	Sierra Nevada Corporation	Water Recovery
Luca	Pietrasanta	University of Brighton	Heat Pipes
Joel	Plawsky	Rensselaer Polytechnic Institute	Heat Pipes
Daniel	Pounds	ThermAvant Technologies, LLC	Heat Pipes
Shahram	Pouya	Iowa State University	Boiling & Condensation
Alex	Povitsky	University of Akron	Heat Pipes
Gabriel	Power	Space Lab Technologies	Water Recovery
Evan	Racine	NASA Glenn Research Center	Boiling & Condensation
Md Mahamudur	Rahman	The University of Texas at El Paso (UTEP)	Boiling & Condensation
Rachel	Rajcsok	Interphase Materials	Boiling & Condensation
Brandon	Reddell	NASA JSC/ISS Program Science Office	Boiling & Condensation
Ryan	Reeves	International Space Station National Laboratory	Boiling & Condensation
Claud	Risner	---	Boiling & Condensation

TABLE B.1.—Continued.

First Name	Last Name	Company	Session
Scott	Roberts	NASA Jet Propulsion Laboratory	Heat Pipes
Ken	Savin	Center for Advancement of Science In Space	Boiling & Condensation
Michael	Schatz	Georgia Institute of Technology	Boiling & Condensation
Jarrod	Schiffbauer	Colorado Mesa University	Boiling & Condensation
Greg	Schunk	NASA Marshall Space Flight Center/EV34	Water Recovery
Brett	Schaffer	Space Lab Technologies LLC	Boiling & Condensation
Parthiv	Shah	ATA Engineering, Inc.	Boiling & Condensation
Rubik	Sheth	NASA Johnson Space Center	Boiling & Condensation
Shanbin	Shi	Rensselaer Polytechnic Institute	Heat Pipes
Shahab	Shojaei-Zadeh	National Science Foundation	Water Recovery
Narsingh B.	Singh	University of Maryland Baltimore County	Heat Pipes
William	Smith	Infinity Fuel Cell and Hydrogen, Inc.	Boiling & Condensation
Noah	Snyder	Interphase Materials	Heat Pipes
Vinod	Srinivasan	University of Minnesota	Boiling & Condensation
Benjamin	Straiton	Tech4Imaging LLC	Boiling & Condensation
Ying	Sun	National Science Foundation	Heat Pipes
Eric	Sunada	NASA Jet Propulsion Laboratory/Caltech	Heat Pipes
Angelantonio	Tafuni	New Jersey Institute of Technology	Boiling & Condensation
Mahsa	Taghavi	University of Houston	Water Recovery
Calin	Tarau	Advanced Cooling Technologies	Heat Pipes
Padetha	Tin	Universities Space Research Association and NASA Glenn Research Center	Heat Pipes
Eugene	Ungar	NASA Johnson Space Center	Boiling & Condensation
David	Urban	NASA Glenn Research Center	Heat Pipes
Subith	Vasu	University of Central Florida, Orlando, FL	Boiling & Condensation
Jonathan	Volk	Space Commerce Matters	Water Recovery
Prashant R.	Waghmare	University of Alberta	Heat Pipes
Erika	Wagner	Blue Origin	Boiling & Condensation
Thomas	Ward	Iowa State University	Boiling & Condensation
Mark	Weislogel	Portland State University/IRPI LLC	Water Recovery
John	Wetzel	Sierra Nevada Corporation	Water Recovery
Dan	White	NASA Glenn Research Center and Case Western Reserve University	Boiling & Condensation
Indrek	Wichman	Michigan State University	Boiling & Condensation
Jarred	Wilhite	NASA Glenn Research Center	Boiling & Condensation
Rube	Williams	Stratos Perception, LLC	Boiling & Condensation
Jiajun	Xu	University of the District of Columbia	Boiling & Condensation

TABLE B.1.—Concluded.

First Name	Last Name	Company	Session
Alexander	Yarin	University of Illinois at Chicago	Boiling & Condensation
Daniel	Yeh	University of South Florida	Water Recovery
Yangying	Zhu	University of California, Santa Barbara	Boiling & Condensation
Greg	Zimmerli	NASA Glenn Research Center	Water Recovery

Appendix C.—Workshop Agenda

The workshop agenda can be found in Tables C.1 and C.2. Presentations 2019 NASA SLPSRA Fluid Physics Workshop are available at http://www.cvent.com/events/2019-nasa-slpsra-fluid-physics-workshop/custom-17-0a98f56ee636488d9bc4675674d50337.aspx.

TABLE C.1.—WORKSHOP AGENDA OCTOBER 16, 2019

Time	Presentation Title	Speaker
Opening Session		
8:30 8:35	Welcome and opening remarks	John McQuillen, NASA Glenn Research Center (GRC)
8:35 8:45	NASA’s Exploration Vision and Reduced Gravity Challenges	Joel Kearns, Director of Facilities, Test & Manufacturing Directorate, NASA GRC
8:45 8:55	Space Life and Physical Sciences Fluid Physics Focused Research Plan	Fran Chiaramonte, NASA Headquarters (HQ)
8:55 9:05	Fluids Physics Program Overview	Fran Chiaramonte, NASA HQ
Water Recovery		
9:05 9:30	Overall Challenges: ISS Water Recovery System,	Layne Carter, NASA Marshall Space Flight Center (MSFC)
	Vapor Compression Distillation Process in Microgravity	Greg Shrunk, NASA MSFC
9:30 9:45	Water Handling Issues in Life Support	Mark Weislogel, Portland State University John Graf, NASA Johnson Space Center (JSC)
9:45 10:00	Packed Bed Reactor Experiment	Brian Motil, NASA GRC
Boiling and Condensation		
10:00 10:25	Spacecraft Power Systems	Raymond Beach, NASA GRC
10:25 10:40	Challenges in Cryogenic Systems	Michael Meyer, NASA GRC
10:40 11:10	JAXA’s Two Phase Flow Experiment	Hitoshi Asano, Kobe University
11:10 11:25	Flow Boiling and Condensation Experiment	Issam Mudawar, Purdue University
11:25 11:40	Zero Boil-Off Tank	Mohammad Kassemi, Case Western Reserve University
11:40 11:50	Thermal Management Systems Reduced Gravity Issues	Eugene Ungar, NASA JSC
Heat Pipes		
11:50 12:05	Overall Challenges	Eric Sunada, NASA Jet Propulsion Laboratory (JPL)
12:05 12:20	Oscillating Heat Pipes	Dan Pounds, ThermAvant Technologies, LLC

12:20 12:30	ESA’s Enhanced Evaporators	Carlo Iorio, Université Libre de Bruxelles
12:30 12:40	ESA’s Pulsating Heat Pipes Experiment	Luca Pietrasanta, University of Brighton
Hardware Presentations		
1:40 1:55	ESA—Heat Transfer HOST 1	Daniele Mangini, European Space Agency (ESA)
1:55 2:10	Flow Boiling and Condensation Experiment (FBCE)	Monica Guzik, NASA GRC
2:10 2:25	Electrohydrodynamic (EHD)	Jeffery Didion, NASA Goddard Space Flight Center (GSFC)
2:25 2:35	Packed Bed Reactor Experiment (PBRE)	Brian Motil, NASA GRC
Breakout Session Topics		
2:45 5:00	Flow Boiling and Condensation	Chair: Brian Motil (NASA GRC) Co-Chair: Jungho Kim (University of Maryland) Co-Chair: Van Carey (University of California at Berkeley) Facilitator: Henry Nahra (NASA GRC), Tyler Hatch (NASA GRC)
	Heat Pipes	Chair: Bill Anderson (Advanced Cooling Technologies, Inc.) Co-Chair: Joel Plawsky (Rensselaer Polytechnic Institute) NASA Facilitator: David Chao (NASA GRC)
	Water Recovery	Chair: Layne Carter (NASA MSFC) Co-Chair: Andrew Jackson (Texas Tech University) NASA Facilitator: Ramaswamy Balasubramaniam (NASA GRC)

TABLE C.2.—WORKSHOP AGENDA OCTOBER 17, 2019

Time	Session Title	Speaker
Breakout Sessions		
8:30 11:00	Breakout Sessions continued	Flow Boiling and Condensation Heat Pipes Water Recovery
Plenary Session		
11:00 12:30	Breakout Session Summary Presentations	Breakout Session Chairs
	Closing Remarks	Fran Chiaramonte (NASA HQ)
1:30 4:30	Chair/Co-Chair Preparation of Draft Workshop Breakout Session Reports	

Appendix D.—RFI Responses

The Request for Information (RFI) responses received were categorized into one or more of the breakout sessions by the workshop organizing committee, see Table D.1 to Table D.3. If an RFI was applicable to multiple sessions, it is listed in order of ranked relevance from high to low.

TABLE D.1.—BOILING AND CONDENSATION REQUESTS FOR INFORMATION

Number	Author(s)	Affiliation	RFI Title
RFI-0001	Sushil Bhavnani	Auburn	Asymmetric Saw-tooth and Cavity-Enhanced Nucleation-Driven Transport (ASCENT)
RFI-0002	Alexander Yarin	University of Illinois at Chicago	Swing-like pool boiling on nano-textured surfaces for microgravity applications related to cooling of high-power microelectronics
RFI-0003	Stuart Williams	University of Louisville	Management of two-phase flow for heat transfer in electronics using electrokinetics
RFI-0005	Leon Brendel	Purdue University	Vapor Compression Refrigeration on the ISS
RFI-0009	Jeffrey Derby	University of Minnesota	Engulfment under flow and solidification
RFI-0010	Saeed Moghaddam	University of Florida	A Novel Two Phase Heat Sink with 1000 W/cm2 CHF at 100% Exit Vapor Quality
RFI-0012	Jeffrey Allen	Michigan Technological University	Advancing knowledge and modeling capabilities of liquid-vapor phase change
RFI-0013	Jungho Kim	University of Maryland	Partial Gravity Effects on Multiphase Flows
RFI-0014	Qussai Marashdeh	Tech4Imaging LLC	Two-Phase Cryogenic Flow Imaging and Measurement using Electrical Capacitance Volume Tomography Sensors
RFI-0015	Thomas Boziuk	Georgia Institute of Technology	Acoustically-Driven Enhanced Two-Phase Looped Heat Transfer
RFI-0019	Alexander Povitsky	University of Akron	Mixing of dissimilar fluids by moving chamber walls
RFI-0020	Paul Steen	Cornell University	Container surface wettability and geometry concept experiments
RFI-0023	Gretar Tryggvason	Johns Hopkins University	Musings on Predictive Capabilities for Multiphase Flows for Reduced Gravity
RFI-0026	Alexander McNamee	Blue Origin	Commercial Suborbital Opportunities for Fluid Physics on Blue Origin’s New Shepard Vehicle
RFI-0027	Shankar Narayanan	Rensselaer Polytechnic Institute	Understanding the Role of Flow Instabilities and Dynamic Heating in Two-phase Systems
RFI-0028	Yangying Zhu	University of California, Santa Barbara	Microgravity boiling enabled by photo-responsive surfactants
	Massoud Kaviany	University of Michigan	Flow Boiling Canopy Wick to Enhance Critical Heat Flux
	Vinod Srinivasan	University of Minnesota	Invariant Quantities in Pool Boiling: A Nonlinear Dynamics Approach to CHF
	Ranga Narayanan	University of Florida	Enhanced Heat Transfer using Faraday Resonance

TABLE D.2.—WATER RECOVERY REQUEST FOR INFORMATION

Number	Author(s)	Affiliation	RFI Title
RFI-0006	Sunghwan Jung	Cornell University	Harvesting water vapors in the air
RFI-0008	Melany Hunt	California Institute of Technology	Three-Phase Microgravity Slurry Reactor for Water Reclamation
RFI-0011	James Ferri	Virginia Commonwealth University	De-emulsification of recovered water using 3dP on-demand process enhancements
RFI-0017	Zhengdong Cheng	Texas A&M University	Water Recovery in Space
RFI-0018	Vemuri Balakotaiah	University of Houston	Bubble Coalescence and Displacement in Porous Media Operations in Microgravity
RFI-0022	Shankar Narayanan	Rensselaer Polytechnic Institute	Understanding Evaporation Near Kinetic Limits
RFI-0025	Giancarlo Corti	Miami University	Superhydrophobic surfaces to condense and collect water

TABLE D.3.—HEAT PIPES REQUEST FOR INFORMATION

Number	Author(s)	Affiliation	RFI Title
RFI-0004	Ying Sun	National Science Foundation	Exploring NASA-NSF collaboration opportunities in the area of heat transfer and fluid dynamics
RFI-0007	Constantine Megaridis	University of Illinois at Chicago	Wettability-Engineered Surfaces for Pumpless, Rapid Fluid Transport in Space
RFI-0016	Dan Pounds	ThermAvant Technologies, LLC	Micro-Gravity and 1-G Testing of Meter-Scale Oscillating Heat Pipes with Out-of-Plane Bends
RFI-0021	Ranga Narayanan	University of Florida	Heat transfer enhancement using resonant mixing
RFI-0024	Jarrod Schiffbauer	Colorado Mesa University	Bottom-up assembly of functionalized nano materials for improved control of thermal and capillary properties of solid and fluid interfaces