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Phase Change Processes for Thermal Management Systems and Science Investigations

Submitted by

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Abstract

This whitepaper focuses on the scientific rationale and motivation for studying phase change processes to improve the performance of next-generation spacecraft thermal management systems, sub-critical cryogenic systems and life support systems. Regarding thermal management, heat transfer rates (per unit fluid mass) for example can be increased by an order of magnitude compared to that associated with single-phase flow by taking advantage of the latent heat of phase change. Moreover, phase change processes can be used to store heat produced during thermal transients. With that said, however, our fundamental understanding of phase change processes is largely based on experimental data acquired at Earth's gravity where buoyancy resulting from density differences often acts on and alters fluid flow and thermal transport involved in phase change processes. As such, there is a strong need for long-duration experimental data on phase-change processes at reduced and partial gravity that can then be used to improve and validate theoretical flow physics models and numerical simulations. The acquired data and validated models will then enable the deployment of game-changing thermal management systems with remarkably improved performance and stability. An improved fundamental understanding of phase-change processes at reduced gravity is also important for space-based cryogenic and life support systems.

Scientific Rationale and Motivation

Phase change processes include solid/liquid transformations such as freeze/thaw behavior, liquid/vapor transformations such as fluid boiling, evaporation and condensation, and solid/vapor transitions such as sublimation and deposition. Phase change processes generally operate far from thermal equilibrium with temperature differences existing between the phases. They are affected by many factors due to the wide variety of working fluids and surfaces involved, often including complicated geometries, e.g., wicking structures. Although some reduced-gravity experiments and studies have been performed [1-4], more data are needed to resolve the many fundamental and practical challenges involved in the design and operation of spacecraft thermal management systems that depend on phase change processes [5-6]. For the next decade, research initiatives should include the acquisition of experimental data and the development of applicable mechanistic models of phase change processes at reduced gravity conditions [7].

Phase change processes involving solid/liquid transformations, such as those used to store energy, are affected by both conductive and convective heat transfer mechanisms. The solid/liquid phase transitions normally involve the presence of a gas to accommodate volume changes from solid to liquid, and vice versa [8-9]. In addition, the melting and solidification processes in flowing systems are much more complicated than those under quiescent or pool conditions. For space-based energy storage systems that take advantage of solid/liquid phase change, it is crucial to develop heat transport materials and systems that provide optimal thermo-physical properties that include high thermal conductivity, long-term stability and reversibility, compatibility with construction materials, non-toxicity, non-flammability, and non-explosiveness [10]. Experimental data are also needed to validate numerical methods that can accurately predict the growth of solidified layers during freezing and the liquefied layer during thawing. In addition, research on void management during freeze/thaw transitions would benefit the design of phase change material (PCM) heat sinks for long-duration microgravity applications.

Phase change processes involving liquid/vapor transformations do not benefit from buoyancy-driven flows at microgravity and, at small length scales, even at Earth's gravity. Other factors such as surface forces dominate. While flow loops can alleviate this limitation, other creative approaches and unconventional forcing methods are needed to create flows needed to enhance heat transfer at microgravity. One such approach is to use resonance forcing or Faraday forcing to create violent flows at interfaces. Such forcing can be achieved by acoustic or electrohydrodynamic means, where feasible. Research into the fluid mechanics of such forcing techniques, the enhancement of heat transfer and the development of models are needed and advocated. Research should include studies on different approaches to induce resonance, the energy input required and the enhancement of heat transfer obtained. Modifications of the FBCE experiment [11] that include multicomponent fluids, resonant forcing such as acoustic or electrohydrodynamic forces would also be beneficial. The science outcomes include clear correlations between forced fields and enhanced phase change for "pool conditions." On the other hand, advanced heat transfer surfaces for ultra-high heat flux applications can be fabricated and tested to enhance liquid/vapor transitions and heat flows at small length scales such as micro- and nano-scales [6]. Data can then be developed at Earth's gravity through comprehensive surface characterization tests and prototype performance tests. The technological outcomes will be new ways to transfer heat in heat pipes without flow loops and will be useful for aerospace technology including hypersonic space travel where heat dissipation from electronics and structures is essential.

Phase change processes involving solid/vapor transformations have received substantially less attention than their solid-liquid or liquid-vapor counterparts. To some degree these processes can be "cleaner" since there is no liquid that can flow into unanticipated areas or support microbial growth. Research is needed to understand how to reversibly confine solid/vapor systems, whether these transformations can be used for thermal management or energy storage or are just important in manufacturing systems, and how to control nucleation for condensation. Since mobility in the solid is limited, void formation and the effects of system cycling are unknown.

Since phase change processes involve latent heat release or absorption, the time scales involved for these changes or to reach steady-state are often long. Transients also take a long time to dissipate. Thus, investigating these processes in drop towers, parabolic flights, and even sounding rockets do not provide sufficient time in microgravity to gather the data required to observe the phenomena, fully understand the key properties and processes involved. Long duration microgravity experiments are essential in this regard. Even machine learning and artificial intelligence techniques could be potentially implemented to help us predict gravitational effects on phase change processes after training with a comprehensive database including experimental data obtained at various gravitational conditions and numerical data from high-fidelity computational simulations.

Finally, many fundamental material properties remain unknown especially in fluid mixtures. Some of these properties include the permittivity and permeability needed to calculate intermolecular forces and the effect of applied fields. Also, fundamentally, we don't understand: (1) the surface excesses at the liquid/vapor and solid/liquid interfaces in fluid mixtures as temperature and composition change, (2) how these surface excesses alter the interfacial tensions, (3) what is the configuration of the liquid molecules at the interface, (4) how does the presence of a second component alter the kinetics of evaporation and condensation, whether the second component is miscible or a permanent gas designed to intentionally modify performance. Moreover, copper porous wicking structures are important for liquid return in heat pipes and other advanced heat exchangers (Figure 1 shows advanced 3D printed copper porous

Figure 1. Copper porous samples fabricated by additive manufacturing.

samples now being developed at Rensselaer Polytechnic Institute). While we can fabricate complex porous structures, the fundamental question: "Of all possible geometries that can be fabricated, which are optimal and why?" is an open issue.

Recommended Research Issues

Experiments, modeling, and numerical simulations are needed in both applied and fundamental fluid physics with considerable emphases on the three phase change processes mentioned above in the next decade. Regarding the experiments, data are needed at micro- and partial gravity and then used to validate critical physical models of phase change processes as well as state-of-the-art numerical simulations. Several research issues are identified as follows.

Development of thermal energy acquisition, storage and transfer using phase change materials (PCM)

- Investigate fundamental, gravity dependent problems including; melting and solidification, void formation, void location, the growth and migration of void bubbles as a function of material properties, gravitational environment, imposed thermal conditions and geometric configuration.
- Develop/apply theoretical models (local thermal equilibrium and non-equilibrium) to predict the thermal profiles and melting and solidification rates of PCM embedded in a conductive matrix such as a fin array or metal foam during heating and cooling cycles and determine, if a conductive matrix geometry that can make the process gravity independent.
- Resolve problems associated with the use of water as a PCM. A thick ice layer within a heat rejection system may also serve as protection from radiation due to solar particle events.

Development of advanced micro- and nano-scale heat transfer surfaces

- Provide ultra-high heat acquisition and dissipation heat flux in phase change heat exchangers and heat pipe loops for advanced power systems cooling and next generation, high performance power electronics needed for space application.
- Develop/apply physics informed tools assisted with advanced machine learning algorithms to design flow channels to increase driving force and minimize flow resistance for two-phase flow systems.
- Investigate evaporation and condensation of high-temperature working fluids in high-temperature heat pipe radiators needed for some nuclear electric propulsion missions [12-13].
- Investigate new forcing techniques for paramagnetic, high temperature materials such as alkali metals.
- Address purification and corrosion issues that result from using high-temperature working fluids.
- Address open issues with contact angles, intermolecular forces, accommodation coefficients and electronic vs phononic thermal transport in both liquid and vapor phases.
- Develop systems and models to handle transients including start-up and shutdown with a focus on freeze/thaw issues. Are there surfaces that can help mitigate the effects of transient three-phase operation?

Development of cryogenic heat pipes

- Investigate materials and fluids to span the gap between He and H_2-based systems. Fluid mixtures may be able to span the working temperature gap. Hydrogen-based systems may embrittle the metals used to contain it.

- Develop geometries that can handle slurry-based operation without clogging for the above-mentioned gap.
- Investigate resonant forcing to enhance operation. Oxygen is paramagnetic so magnetic forcing is possible.
- Cryogenic fluids are generally perfectly wetting. The design of efficient wicking structures, accommodation coefficients, resistances across the vapor-liquid interface, and containment systems are important areas of research.

Investigation of other simulant fluids for ground tests

- Develop simulant fluids for high temperature heat pipes. Metal eutectics, ionic liquids, should be investigated as safer simulants.
- Develop simulant fluids to investigate three-phase operation at near room temperature. T-butanol has a narrow temperature range between freezing and boiling that exists around room temperature. Other fluids or fluid mixtures should also be investigated.

Fundamental science studies of phase change using microgravity platforms

- Use the FBCE or equivalent apparatus in a non-forced pumped flow mode to study multicomponent Benard-Marangoni and evaporative instability physics without interference from buoyancy driven convection. Attention is also needed on dry-out and long wavelength instabilities. Such studies would throw light on preventing dry-out and would find use in the making of smart surfaces.
- Use microgravity platforms to study resonance induced instability effects on phase change. This would include the use of mechanical, electrodynamic or acoustic force fields [14-15]. Hypotheses could be investigated such as **suppressing instability** when the liquid phase is the hotter than the vapor phase and **enhancing instability** and flows when the vapor phase is the hotter phase. Such studies have potential use in small scale heat pipe control.
- Use microgravity platforms to levitate aqueous drops and induce phase change via vapor heating with inerts, then study the fluid physics such as Marangoni convection in spherical fluid bodies with phase change.

Summary

Understanding phase change mass and heat transport is critical to safe operation of thermal management systems implementing highly efficient phase change processes for space missions. Multiple research issues are summarized in this white paper to motivate more comprehensive research activities to advance the deployment of future thermal management systems. Vast-quantity and high-quality experimental data in various gravitational conditions are needed to systematically understand the scientific fundamentals and elevate relevant Technology Readiness Levels (TRL) at NASA.

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