

TOPICAL: BOILING, CONDENSATION AND TWO-PHASE FLOWS IN MICROGRAVITY

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Abstract

The white paper addresses both fundamental and technological questions in the science of phase-change fluid flows aimed at understanding thermal transport in flow boiling and condensation and the use of these processes in space and terrestrial thermal systems. While flow boiling and condensation are widely employed in Earth-based thermal equipment to reduce the cost, size, and power required to transfer heat, a lack of data and predictive models on the impact of gravity on these phenomena hinders the use of two-phase heat transport in a low-gravity environment. The white paper presents research tasks in long-duration microgravity recommended to expand our knowledge on phase-changing flows. Due to elimination of the masking gravity effects, the proposed research will provide a unique opportunity to bring new insights into the role of capillary and hydrodynamic forces in phase-changing flows. The potential impact of the proposed research ranges from the space power, thermal and cryogenic systems to various terrestrial applications in the petrochemical, pharmaceutical, biochemical, nuclear, and metallurgical industries.

Scientific rationale and motivation

Boiling heat transfer involves the evaporation of liquid in a hot region and condensation of vapor in a cold region. By exploiting the latent heat of vaporization, boiling and condensation can transfer up to several orders-of-magnitude more heat compared to forced liquid flow. While boiling and condensation are widely used in Earth-based thermal equipment to reduce the cost, size, and power required to transfer heat, a lack of data and predictive models on the impact of gravity on these phenomena hinders the use of two-phase heat transport in a low-gravity environment [1-3]. Flow boiling is especially important in spacecraft and habitat thermal control systems and power systems [1-6]. On the other hand, boiling flow is an adverse event in space cryogenic fluid systems which are subject to heat loads from a variety of sources, such as incident solar radiation, albedo of celestial bodies and heat generated by equipment [7-11]. Both self-pressurization of cryogenic propellant tank and the performance of its active pressure control systems are significantly affected by the intricate evaporation and condensation that takes place at an evolving liquid-vapor phase front under microgravity conditions. During tank-to-tank transfer and/or engine operations, space cryogenic fluid management requires vapor-free liquid delivery that is impacted by the time- and location- dependent liquid-vapor flows of cryogenic fluids that are made complicated due to the very low boiling point in most applications [5-11].

Due to complex interactions between the flow field and liquid-vapor phase transitions, flow boiling and condensation often exhibit transients and instabilities caused by the slow propagation of pressure disturbances in two-phase regions, the accumulation of vapor downstream from the locally heated sections, and the coalescence and collapse of vapor bubbles [12-16]. The coupling between low-frequency pressure disturbances and mechanical vibrations can amplify these instabilities [17]. Thermal-hydrodynamic disturbances may decay and lead to normal operation or may generate large-amplitude flow oscillations and hydraulic shocks (*fluid hammer*) disturbing the flow and thermal control and causing mechanical damage. While there are many models describing and correlating flow boiling and condensation instabilities under normal gravity, the gravitational mechanisms driving these phenomena will not be present in microgravity. Moreover, compared to the normal gravity environment, phase-changing flows in microgravity are much more complicated due to the uncertain distribution of the liquid and vapor distributions within a system under unsettled conditions

The brief outline above demonstrates that two-phase flows involving multiple liquids and vapors are present in many current and proposed space systems, such as heat exchangers, thermal control, power systems, heat pipes, cryogenic fluid management, cryogenic propellant storage and transfer, phase separators, fuel cells and water management. The role that flow boiling and condensation plays in a variety of these space systems makes accurate prediction of these phenomena in key exploration technologies to be critically important for human exploration missions to the Moon and Mars [1-6]. Understanding of phase-changing flows in reduced gravity is therefore of highest priority for enabling new exploration capabilities and finding new insights into a broad range of physical phenomena in space and on Earth [18-39].

Modeling of phase-changing flows in microgravity is the area of particular interest. The computational models should be able to solve the flow, energy, mass, and species equations under conditions of separated bulk phases such as an ullage-liquid system in a sealed tank or for interpenetrating phases that occur during the different boiling and condensation regimes that may be encountered in microgravity [40-45]. For separated bulk phases, Eulerian Computational Fluid Dynamics (CFD) schemes using Volume of Fluids (VOF) and Level Set (LS) methods are usually applied to capture the evolving and deforming liquid vapor interface in microgravity. To capture

the interpenetrating phases, Eulerian Multi-fluids methods and in some cases Eulerian-Lagrangian Discrete Particle Methods (DPM) are needed. In both cases, microgravity data is needed to verify and validate these complex computational models and the associated CFD Codes. The formulating empirical-based closure relationships that are used in the multi-fluids CFD methods require extensive microgravity experimentation.

Extensive studies have also been conducted for over seventy years to develop, test and validate predictive system level (nodal) models and computer codes for simulations of flow and heat transfer in two-phase systems under normal gravity as they occur in various applications in the petrochemical, pharmaceutical, biochemical, nuclear, and metallurgical industries. Due to the level of complexity in the phenomena, simple theoretical models and intuition are not capable of predicting the response of two-phase flow systems to unexpected transients and perturbations, such as loss of coolant accidents through the rupture. The state-of-the art simulation codes, commonly used by the nuclear industry, such as RELAP (Reactor Excursion and Leak Analysis Program) from the Idaho National Laboratory (INL) [46] and JTopmeret code from GSE Solutions [47] can be used for simulating the response of two-phase thermal-hydraulic systems in real and hypothetical transient scenarios to help form the strategy for decisions made concerning system design, active control, operation, and safety. The U.S. Nuclear Regulatory Commission routinely uses these system level thermal-hydraulic codes in the design and operation of boiling and pressurized water reactors and to employ machine-learning algorithms to detect process anomalies and mitigate the issue [48].

The verification of the design of a large-scale two-phase flow system for thermal and cryogenic flow management in space applications requires expensive and risky experiments in the microgravity environment. The advantage of advanced thermal-hydraulics codes is the capability to scale up phenomena observed in small-scale test facilities to full size systems as they take a component-based approach to modeling the entire system, like a nuclear power plant. The replacement of experiments by numerical analysis will need dedicated experiments in microgravity to support the development, testing and validation of computer models for microgravity environment. These models should be based on detailed numerical simulations of phase-changing flows in reduced gravity data and should be capable of accurately scaling up so that they can be used to design and operate hardware of spacecraft and extraterrestrial habitats.

Need for long duration microgravity

Current knowledge of thermal transport in phase-change fluid flows rests on over a century of experiments conducted under Earth's gravity. It is of limited use for predicting flow boiling and condensation behaviors in microgravity where there is no buoyancy and the processes are governed by a balance of inertial, viscous, and interfacial forces. Research on phase-changing flows in reduced-gravity is needed for the development of the fundamental fluid physics understanding that is required for the advancement of technologies for numerous space applications. Due to elimination of the masking gravity effects, the research in long duration microgravity will provide a unique opportunity to bring new insights into the role of capillary and hydrodynamic forces in phase-changing flows in Earth-based systems.

Current knowledge of thermal transport in phase-change flows in reduced gravity has been amassed over sixty years by performing tests in drop towers, parabolic aircraft flights, and sounding rockets [18-39]. Due to a brief exposure to reduced gravity, 1-5 s in drop towers, 12-17 s per aircraft parabola, and 6-13 min in rockets, extensive studies on these platforms have elucidated gravity's effects only over relatively short periods of time. Most of the longer term

experiments on Space Shuttle missions and the early tests on the International Space Station (ISS) focused on pool boiling. All these studies have demonstrated that a balance between inertial, viscous, and interfacial forces in the absence of gravity drastically changes the nature of phase-change flows. Under such conditions the evolution of the liquid-vapor structures is much more prolonged and complicated. Nucleated bubbles in these flows are observed to slide over the heater, detach due to vapor recoil, and hover close to the heater surface as they coalesce with satellite bubbles. Eventually the heat flux reaches a maximum, termed the critical heat flux (CHF), when bubbles growing in adjacent sites merge together to cover the heated surface with a vapor blanket that dramatically reduces heat transfer. Due to very low CHF values, pool boiling is not viable for thermal management in space systems. Since experiments on heat transfer in flow boiling and condensation require a high heat load, a large space for the test apparatus, and a significantly longer measurement time, very few studies of flow boiling and condensation under low gravity have been conducted so far, mostly due to limited experimental facilities. The available correlations and models are unable to provide reliable data for prediction of nucleate boiling and critical heat flux in fluid flow under reduced gravity.

For example, experiments in long duration microgravity on the International Space Station (ISS) revealed that Marangoni forces can dominate the operation of a heat pipe in microgravity (Fig. 1) [49-51]. It was observed that flooding of the heated end in a heat pipe that grew worse with heat input due to a collision of Marangoni and capillary forces.

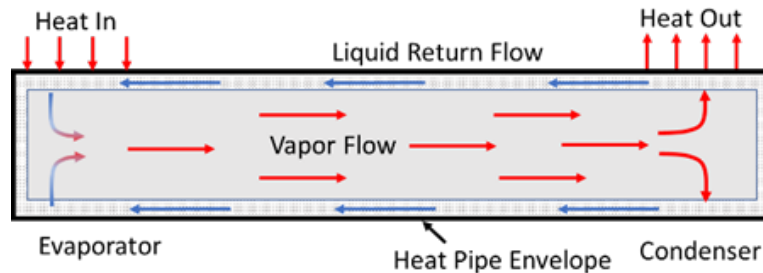


Figure 1. Wickless heat pipes in microgravity [49-51]

Furthermore, the two phase phenomena that govern, self-pressurization and pressure control of cryogenic storage tanks through forced jet mixing or droplet injection, and the complicated time dependent mechanisms that occur during tank-to-tank transfer and the line and tank chill-down operations cannot be elucidated by the short term ground-based microgravity facilities and require long-duration microgravity experimentation [4,5]. In this context, as shown by the recently flown Zero-Boil-Off Tank (ZBOT) experiment, long-duration microgravity two phase flow and heat transfer experiments are also indispensable for obtaining the reliable data needed to develop, test and validate theoretical models and computer codes that will be ultimately used for predicting the performance of the various space systems. The ZBOT investigation [52-55] resulted in roughly 30 tank self-pressurization and pressure control model validation studies against microgravity data an example of which is shown in Fig. 2.

The main goal of the ongoing NASA project lead by Dr. Mudawar (Purdue University) and Dr. Hasan (NASA GRC) is to develop an integrated Flow Boiling and Condensation Experiment (FBCE) Hardware facility for the ISS to serve as a primary platform for studies of two-phase flow and heat transfer data in microgravity [56,57]. The ISS Boiling and Condensation Experiment (FBCE) Hardware will provide the unique platform required for the proposed research and eliminating all the limitations associated with previous experimental efforts in reduced gravity.

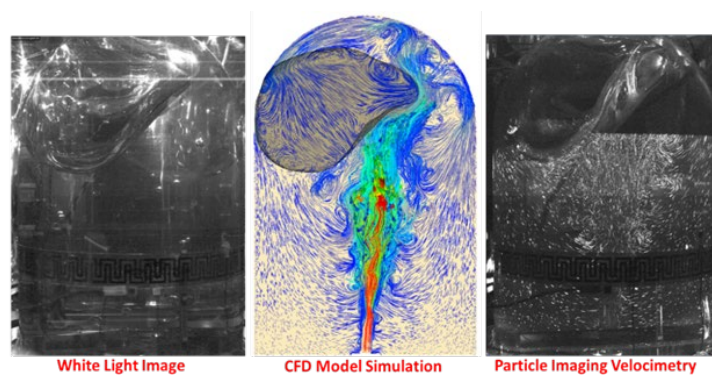


Figure 2. Zero-Boil-Off Tank (ZBOT) experiment: Depiction of fluid flow and deformation of Ullage (vapor bubble) by the liquid jet during forced jet mixing pressure control in microgravity [52-55]

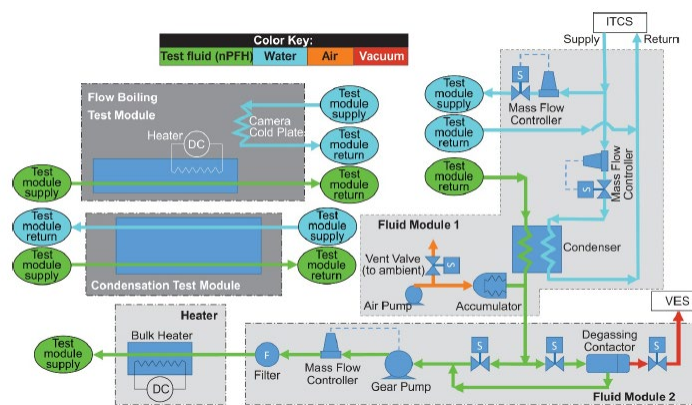


Figure 3. FBCE connected to vacuum exhaust system (VES) and internal thermal control system (ITCS) [56].

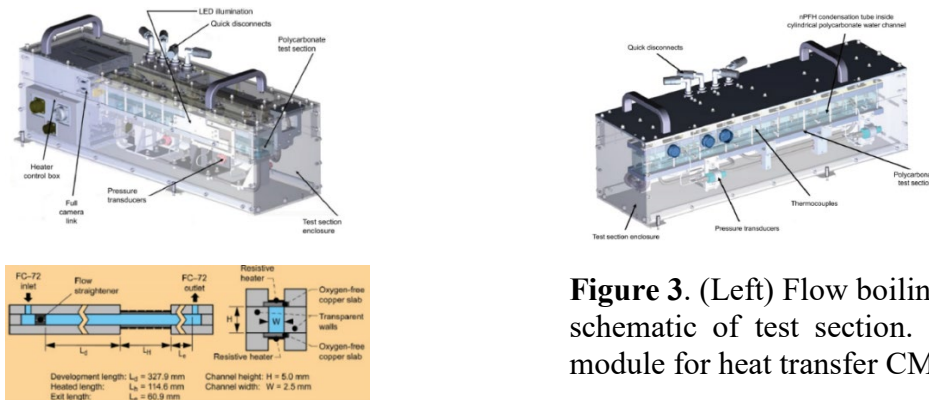


Figure 3. (Left) Flow boiling module (FBM) with schematic of test section. (Right) Condensation module for heat transfer CM-HT [56]

By eliminating strong buoyancy effects, long-duration microgravity experimentation also offers a unique opportunity to refine the role of capillary and hydrodynamic forces in phase-changing flows and bring new insights into flow boiling and condensation phenomena on Earth as they occur in various applications in the petrochemical, pharmaceutical, biochemical, nuclear, and metallurgical industries.

Recommended research in long-duration microgravity

The proposed experiments on flow boiling and condensation in long-duration microgravity are of fundamental importance for understanding the role of inertial, viscous and interfacial forces on

the dynamics of liquid-vapor phase transitions. They will provide reliable data for a wide range of gravity-related challenges in space and terrestrial applications, such as cryogenic propulsion, in-space fueling systems, storage, fluid and heat transport, and handling of cryogenic and medical fluids, water treatment, and control of environmental conditions in space and Planetary habitats.

We recommend experimental, analytical and numerical investigations to study the gravity effect on evaporation and condensation in phase-changing flows in single and multiple channels or sealed tanks with and without porous wicking materials, for fluid properties encompassing the broad range from cryogenic to liquid metals needed to define/characterize/quantify/predict the following phenomena in microgravity:

- What are the conditions for the inception of boiling and what is the minimum flow velocity needed to sustain or suppress the flow boiling?
- How to modify the current mechanistic models which were developed based on terrestrial experiments to predict the formation, growth, and departure of a vapor bubble in flow boiling on a heated surface when buoyancy is absent and the bubble behavior is governed by inertial, viscous, and interfacial forces?
- How to evaluate the effect of flow velocity on the nucleate boiling and film boiling heat transfer coefficients, maximum and minimum critical heat fluxes and wall superheats at critical conditions?
- Would the flow patterns in flow boiling and condensation be similar to three basic axisymmetric flow patterns (bubbly, slug and annular) observed in adiabatic gas-liquid pipe flows under low gravity?
- Would the forward and backward transitions between different patterns of phase-changing flow depend on the heating and cooling rate and how to control the desirable flow pattern in boiling and condensation?
- How to modify the current stability maps which were developed based on terrestrial experiments to design stable and safe thermal management systems and predict the transients and flow response to inevitable mechanical and thermal disturbances in the absence of buoyancy?
- What is the role of transport and kinetic effects of non-condensable gases on condensation at a vapor liquid interface and on a sealed tank depressurization?
- Does a non-condensable transport barrier form in a vapor bubble and how effective it is in the impeding of interfacial mass transfer, formation of thin films and transport during condensation?
- How to predict liquid atomization/disintegration during liquid injection, transport of droplets, droplet evaporation, and the interaction of droplet with a wall and/or with a liquid-vapor interface when buoyancy is absent?
- Is the Leidenfrost effect strong enough to propel droplets away from a heated surface in a storage tank?
- Can cavitation occur due to rapid depressurization in a sealed tank?
- Find creative ways to enhance flow in heat pipe configurations without using flow loops and pumps. This will be particularly useful for micro-heat exchangers that will be useful in aerospace applications

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