Research Campaign

Overcoming the Scientific Challenges of Microgravity Two-Phase Flow for the Development of Transformative Zero-Boil-Off Cryogenic Propellant Storage and Transfer Space Technology

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Abstract

Significant advancement beyond the current state of the art in management of cryogenic propellants in Space is needed to use cryogens as a viable propellant in higher performing nuclear thermal propulsion or even the highest performance chemical propulsion systems for future exploration missions. To bring about this advancement, the aerospace community has converged on the transformative Zero-Boil-Off (ZBO) strategy to achieve reliable, cost-effective, efficient, and lossless propellant storage and transfer in Space. But before such a complex technology can be fully developed, implemented and demonstrated in Space, important and decisive scientific questions regarding the multiple gravity-dependent interacting phase change and transport phenomena that affect the performance of the propellant tank system in microgravity must be delineated and resolved.

In this white paper, we recommend a comprehensive multiplatform research campaign to achieve this goal. This campaign consists of a series of hierarchical small- and medium-scale microgravity science experiments with both simulant and cryogenic fluids to acquire unique microgravity science data. In parallel high-fidelity computational models will be also developed based on the delineated physics and validated by the detailed microgravity data provided by state-of-the-art whole-field diagnostic techniques.

The cohesive scientific undertaking advocated here for advancement of space-based cryogenic two-phase systems is akin, in scope and impact, to the comprehensive scientific effort that was successfully undertaken by the Department of Energy to bring transformative advancements in the efficiency, safety, and reliability of two-phase water-steam systems for ground-based nuclear technologies. The state-of-the-art experimental-computational-diagnostics approach to be followed aims at elevating the microgravity two-phase experiments to the level of fidelity and accuracy enjoyed by ground-based investigations focused on fundamental fluid physics discovery.

We decide today whether this will be the reality tomorrow .....

****Figure link: https://medium.com/spaceinmylifetime/how-spacex-will-refuel-on-the-surface-of-mars-3438bcc2aefe**

1. Introduction

NASA's vision for returning crew to the Moon in a sustainable manner, followed by human missions to Mars, is a daunting challenge. Since Space is not only an exploration frontier but a commercial and military one, as well, this challenge also extends to national security and defense arenas[1,2]. As testified by the senior advisor to NASA Administrator, Bhavya Lai, before the US House Space & Aeronautics Committee: "[US] strategic competitors, including China, are aggressively investing in a wide range of Space technologies including nuclear power and propulsion to fulfill their ambitions for sustained human lunar presence as well as Martian and deep-space missions …. US needs to be tooled at a fast pace to remain a leader in the global space community"[3].

Countless mission studies by NASA and its industry partners have pointed to cryogenic propellants as a required element for meeting the challenges of chemical and nuclear thermal propulsion for long duration missions[3-17]. However, to use cryogens as a viable propellant, significant advancement beyond the current state of the art in Cryogenic Fluid Management (CFM) of propellants in Space is needed to: (a) allow in-space and on-surface propellant preservation for years rather than hours; (b) eliminate wasteful continuous firing of settling thrusters for liquid propellant acquisition and vapor venting; and (c) enable propellant transfer to and from space depots for refueling of spacecraft that has never been demonstrated in Space. These advancements will have a significant transformative impact enabling the use of higher performing nuclear thermal propulsion (liquid hydrogen) or even the highest performance chemical propulsion for the future exploration spacecraft[14-17]. Thus, dramatically reducing mission costs through smaller vehicles and increasing mission reliability and crew safety by shortening mission durations. In this while paper a scientific research campaign to achieve this transformative advancement in Space CFM is presented. It is anticipated that this research will be carried out by a consortium of universities and aerospace companies led by NASA.

2. Scientific Rational & Motivation

To realize this vision, the aerospace community has converged on a Zero-Boil-Off (ZBO) or Reduced Boil-Off (RBO) strategy[18-23] for CFM of future space-based propellant storage and transfer technologies[6-8,22]. Unlike the short duration gravity-insensitive passive pressure control systems, used to date, the future ZBO and RBO pressure control strategies, will rely on a complex combination of active mixing and energy removal from the two-phase multi-component propellent system[20,23-25] that is governed by multiple interacting phase change and transport mechanisms that are significantly affected by the gravitational field[24]. *The two past National Academy of Sciences Decadal Surveys[26-27] have strongly emphasized the importance of scientific research in this area and recommended that before a large and quite costly space demonstration of this complex technology can be successfully realized, a series of small-scale microgravity science experiments are needed to provide direct and relevant high-fidelity data across the gravitational continuum: from high-g to 1g, and through partial-g to microgravity.* These experiments must be focused on:

(a) acquiring a sound scientific understanding of the impact of weightlessness on the intricate interplay between the governing two-phase physical mechanisms;
(b) deriving empirical correlations for quantification of various transport and phase change mechanisms and their time constants in microgravity;
(c) developing predictive two-phase computational fluid dynamics (CFD) models that are based on first principal physics together with empirically-based system level engineering models for rapid design calculations; and
(d) comprehensive validation of the computational models against detailed measurements collected with state-of-the-art nonintrusive diagnostic techniques for whole-field velocity, temperature, and phase distributions.

2.1 Important Elements of Cryogenic Fluid Management in Space

The future Cryogenic Fluid Management (CFM) operations of propellant tanks in Space can be divided into two broad categories: Propellant Storage and Propellant Transfer.[28-31]

Propellant Storage: The most compelling storage issue is ***self-pressurization*** of the propellant tank caused by heat leaks that if left uncontrolled can lead to structural failure due to excessive pressure build-up[32-33]. Since the traditionally used continuous venting is not a viable option for long-duration storage, ZBO or RBO design strategies must be employed to control the self-pressurization using ***active mixing and cooling***[25,28-30] to preserve the cryogen. Storage is further complicated by the existence of ***noncondensable gases***[34] in the ullage that can impede pressure control[29] and by ***liquid sloshing***[35-37], that is caused by sudden accelerations and can lead to ullage/pressure collapse and/or cavitation. Although the physical phenomena that influence ZBO/RBO tank pressure control are highly gravity-dependent, these processes have not been adequately assessed, tested, or attempted in microgravity. Finally, ***Liquefaction*** of the gaseous propellant is required for production of life support and propellant fluids through In-situ Resource Utilization (ISRU) in partial-gravity or even possibly in micro-gravity[38]. Liquefaction is affected by natural-convection, wall condensation, and film formation that are all gravity-dependent.

Propellant Transfer: Propellant transfer with zero or near-zero cryogen loss is crucially important in space depot refueling operations and for routine engine start-ups[28-30, 39]. Since failure of transfer pumps is a concern, NASA is focusing on less risky ***autogenous***[40-42] or ***noncondensable gas pressurization***[43-45] of the donor tank in microgravity for liquid extraction. Donor tank operations are burdened by requirements of ***liquid-free venting*** and ***vapor-free liquid extraction*** using liquid traps, liquid acquisition devices (LAD)s and propellant management devices (PMD) that are not easily achievable for cryogens in Space due to their complex phase change and transport issues[46-51]. Finally, for tank-to-tank transfer both the support lines and the receiver tank must be cooled by sacrificing some of the cryogen to perform complex ***line and tank chill-down***[53-54] followed by ***no-vent tank filling operations***[57-56] that involve gravity-dependent transitions between boiling regimes not adequately characterized in microgravity.

2.2 Fundamental Physical Phenomena to be Investigated in Microgravity

Propellant self-pressurization is governed by the intricate interactions between gravity-dependent natural convection and the evaporation-condensation mass transfer processes at the phase front[32-33,57-65]. In microgravity, these interactions are more complicated as a moving/deforming interface responds to residual and transient accelerations, surface tension forces and capillary forces at the solid-liquid-vapor contact-line [66-69]. The stability of the interface can be suddenly disrupted due to liquid slosh caused by sudden transient accelerations with a grave possibility of tank depressurization and ullage collapse due to massive phase change[70-73].

These complications can be mitigated through active ZBO or RBO pressure control strategies involving mixing and cooling of the fluid. A prominent strategy is based on use of an intermittent forced subcooled jet flow[25, 67-69, 74-79]. Microgravity jet mixing data is needed across a wide range of scaled parameters to characterize the time constants for tank pressure reduction, and the thresholds for geyser formation, its stability, and its penetration depth through the ullage,

The low viscosity of the cryogenic fluids (e.g. hydrogen, oxygen, and methane) and the large dimensions of the storage tanks lead to turbulent natural and forced jet flows for typical, high-g, 1-g, and partial-gravity applications and even for the depot-size tanks in microgravity[65,71,75,78]. Both low-g (unsettled phases) and 1-g (settled phases) data are needed to develop semi-mechanistic empirically-based *law-of-interface* turbulent models to correctly capture the effect of turbulence on the condensation and evaporation heat and mass transfer at non-stationary interfaces[79-80].

Active pressure control can also be accomplished via injection of subcooled liquid droplets through an axial spray-bar directly into the ullage[81-84]. Liquid injection can also be used to cool down the tank wall before a charge-vent-hold filling operation[56,85]. Liquid disintegration into droplets, their physical transport and phase change across the ullage, their impingement on a hot wall leading to flash evaporation and complications caused by the Liedenfrost effects are all complex phenomena that have not been scientifically examined in microgravity[85-87].

Noncondensable gases (NCG)s are used as pressurants to extract liquid for engine operations and tank-to-tank transfer[34,74,88-92]. Due to reduced solutal convection in microgravity, NCGs can accumulate to create both a transport barrier[34,74,88] and possibly a kinetic resistance[89-90] at the liquid-vapor interface reducing the condensation rates significantly[91-92]. They can also instigate a unique and less understood class of Marangoni convection that is generated by partial pressures on the vapor side rather than by the thermal gradients in the liquid[93-94]. This may divert the cooling jet flow away from the interface. NCG effects will be both more pronounced and more readily revealed to be scrutinized in weightlessness. Ultimately, these effects may prevent the subcooled jet mixing to serve as a viable tank pressure control strategy[91].

In microgravity, the possibility of nucleate pool boiling at the wall is greatly enhanced due to the weakening of natural convection. Pressure spikes caused by pool boiling in a sealed tank may be large and explosive in microgravity endangering the tank's structural integrity[95-96]. Despite recent microgravity experiments and theoretical treatments, pool boiling sublayer characteristics and regime transitions have not yet been adequately examined in the context of a sealed pressurized cryogenic fluid[97-106]. The same considerations also hold for flow boiling that is commonly encountered during propellant transfer processes where feedlines must be chilled down before transfer operation can be initiated[52-54, 106-113].

3. Recommendations for Future Multiple Platform Research Investigations

Due to the wide range of gravity dependent phenomena that must be investigated, a campaign of multiplatform experiments, computational model development, and diagnostic techniques is recommended and described below.

3.1. Small Scale Simulant Fluid Storage & Transfer Experiment Series on ISS

A comprehensive series of small-size (~10 cm diameter), transparent, simulant-fluid science experiments are recommended below that can be fitted into the Microgravity Science Glovebox (MSG) or the Fluids Integrated Rack (FIR) aboard the ISS. The simulant fluids experiments are less costly to develop and easier to perform due to their near room temperature boiling points. Moreover, because of their transparency, they can benefit from a range of readily available nonintrusive whole-field scientific diagnostics for computational model validation. The objective of these experiments will be to answer the following fundamental science questions based on a series of hierarchical experiments.

I. Self-Pressurization & Jet Mixing Experiment

(a) What are the stationary and transient self-pressurization and thermal stratification rates in microgravity? (b) How is the self-pressurization rate affected by sudden acceleration? (c) Can liquid sloshing lead to rapid depressurization and ullage collapse? (d) What are the jet-ullage interactions under laminar, transitionary, and turbulent regimes? (e) What are the geyser penetration depths and stability criteria in microgravity for low, medium, and large Weber numbers? (f) What are the thermal destratification/depressurization rates during subcooled jet mixing? (d) Is ZBO control of tank pressure feasible using mixing or subcooled mixing? (h) Can ZBO subcooled mixing pressure control lead to depressurization cavitation?

II. Noncondensable Gas (NCG) Effects Experiment

(a) What are the transport and kinetic effects of non-condensable gases on condensation and associated depressurization? (b) What is the effect of the diffusive transport barrier at the liquid/vapor interface? (c) What is the impact of non-condensable gasses on condensation mass transfer by penetrating the Knudsen layer? (d) Can NCGs instigate a unique partial pressure driven

Marangoni convection? (e) Will the Marangoni convection be able to divert the liquid jet away from the interface? (f) Do noncondensable gases lead to cavitation at screens or hot spots in microgravity? (g) Is axial jet mixing a viable depressurization strategy in presence of NCGs?

III. Droplet Phase Change Pressure Control Experiment

(a) How is liquid atomization/disintegration different in 0g? (b) How is transport and residence time of droplet across the ullage affected by weightlessness? (c) What is the effect of droplet evaporation on tank pressure? Is it affected by non-condensable gases? (d) How is droplet-wall and droplet-interface interaction modified in 0g? (f) What are the pressure and heat transfer effects of flash vaporization on the walls? (g) Is the Leidenfrost effect strong enough to propel droplets away from the wall in 0g? (h) How are wall condensation and film formation different in 0g?

IV. Ventless Tank-to-Tank Transfer Experiments

Donor Tank: (a) What are the implications of bubble point pressure under isothermal conditions for a screen-mesh LAD? (b) Do heat transfer conditions affect LAD vapor breakthrough in microgravity? (c) What are the criteria for LAD failure in microgravity during liquid extraction?

Receiver Tank: (a) How are bubble nucleation, growth, sliding, and departure frequency and diameter different during nucleate pool boiling in microgravity (b) What are the pool boiling regimes and transitions during tank chilldown? c) What are the stability criteria for isothermal/non-isothermal single-phase/two-phase tank filling? (d) What are the integrated system level dynamics of a two-phase two-tank system in microgravity?

Transfer line Flow Boiling: how are the flow boiling regimes transitions during line chill down affected by microgravity?

3.2. Medium-Scale Cryogenic Storage & Transfer Experiment on a Free-flyer Platform

Although the fundamental transport and phase change phenomena are the same for simulant and cryogenic fluids, establishing complete similitude between cryogenic and simulant fluid experiments will be difficult due to the existence of the numerous dimensionless scaling parameters. Thus, to anchor the numerical models across fluid types and dimensional scales for greater and more precise fidelity and for ultimately incorporating the experimental results into future propellant tank design, it is imperative to conduct the counterparts of Experiments I to IV above in a scaled-up version (~ 0.50 meter diameter tank) using a moderate range cryogenic fluid such as LN2 or LCH4. This is can be accomplished by a single comprehensive medium-scaled cryogenic experiment performed either connected externally to ISS or on a Free-flyer platform.

3.3 Ground-Based 1G and Reduced-Gravity Experiments

Ground-based investigations and short duration reduced gravity facilities can still be used to significant advantage, for complimenting the ISS/Free-flyer research in a cost-effective manner:

- 1G investigations: Pre- or Post-flight experiments corresponding to flight test matrices for anchoring model validation; interfacial turbulence investigations,
- Drop Tower: jet-ullage geyser penetration, contact line dynamics, and cavitation experiments,
- Suborbital/Sounding Rocket: Liquid traps, LADs, PMDs, mass gauging, partial-g liquefaction.

4. State-of-the-Art CFD and System-Level Model Development & Validation

Development of validated computational models that can simulate the performance of propellant tanks in microgravity is an area of particular interest and focus. These models can accelerate the design and scaleup of the future propellant systems by eliminating the inefficient design-build-test-fail-redesign cycles, resulting in lower costs, reduced risks, and earlier exploration missions. These models will also prove indispensable for identifying the causes of future malfunctions that may occur during depot or spacecraft tank operations and will help in devising engineering countermeasures and remedies for their recovery.

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 complex boiling and condensation regimes encountered in microgravity. It is recommended for these models to be developed by incorporating in-house formulated User-Defined-Functions (UDF)s or submodels into the framework of industry-standard or open source CFD codes such as Ansys-Fluent, Star-CM, Flow-3D or OpenFoam. In this manner, the CFD codes will be enhanced effectively through inclusion of the missing or neglected physics by submodels that are developed and validated by the PI Teams. But once distributed for use by third parties, the model/code can enjoy the benefits of independent and strong user support provided by the software/code companies or by the open source communities. This approach can transform the way NASA and industry develop future transportation systems. Three classes of computational models are envisioned.

I. Two-Phase CFD Models for Separated Phases: These include 3D CFD schemes that use interface capturing techniques, such as Volume of Fluids (VOF)[114] and Level Set (LS)[115] methods, to track the evolving and deforming liquid vapor interface and Discrete Particle Methods (DPM)[116] that track droplets and bubbles in microgravity with little empirical-based inputs.

II. Multi-Fluids CFD Models for Interpenetrating Phases: 3D Multi-fluids methods[117-118] are needed to capture the complicated interpenetrating phases. These models combine a first principle framework and formulation with empirical inter-phase/inter-fluids closure laws to deal with quite complex fluid type transitions involving such phenomena as wall boiling, bubbly flows, mist flows, and etc. These models require a dedicated set of associated experiments in microgravity to provide the inter-phase closure correlations with fidelity.

III. System-Level 1-D Models for Integrated Tank -to-Tank System Design: Simulations of CFM processes during full mission scenarios are only possible through temporal and spatial couplings between the computationally intensive 3D CFD models and the more agile 1D system level models. The existing nuclear industry multiphase system-level codes[119] such as RELAP (Reactor Excursion and Leak Analysis Program)[120], from the Idaho National Laboratory, can be used to this end with great advantage. But it must be extensively customized for propellant tank CFM applications with correlations derived from microgravity fluids experiments recommended for this campaign.

5. Development of State-of-the Art Scientific Diagnostics for Cryogenic Fluids

For transparent simulant fluids, The ZBOT-1 experiment underscored the value of the Digital Particle-Imaging-Velocimetry (DPIV) diagnostics in revealing the detailed vortex structures and jet flow behavior in microgravity which guided the model development/validation process[75]. Quantum Dot Thermometry (QDT) is currently under development for full field temperature measurements in the follow-on ZBOT-NC Experiment[121-126]. It is imperative that a serious undertaking be also devoted for the development of advanced whole-field mapping of temperature, velocity, and phase distributions for candidate cryogenic fluids such as nitrogen and methane[127-128]. These tools are needed to elevate the microgravity experiments to the level of precision enjoyed by ground-based investigations focused on fundamental fluid physics discovery.

6. Closure

This whitepaper presented a comprehensive multiplatform microgravity research campaign for creating the much-needed scientific foundation for the development of transformative cryogenic propellant storage and transfer space technologies. A tentative schedule of the experiments to be carried out by BPS is presented at the link below (Ctrl + Click here). Due to the important applications of the scientific findings, it is hoped that this research can take place with close coordinations between NASA BPS and STMD and between NASA and Department of Energy so that the scientific findings and computational models can get infused from early on into technologies that promote future exploration in Space and the future hydrogen energy economy on Earth.

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Research Campaign Timeline