SPACE
{Editorial Insights}

Cryogenic Propellant Thermal-Fluid Management for Chemical and Nuclear Spacecraft Propulsion: Importance, Physics, and Zero-Boil-Off Strategies

Jacob Nan-Chu Chung*

*** Correspondence: jnchung@ufl.edu, Department of Mechanical & Aerospace Engineering, University of Florida**

Abstract: Cryogenic propellants such as liquid hydrogen (LH_2), liquid oxygen (LOX), and liquid methane (LCH_4) are critical to high-performance chemical and nuclear propulsion systems. However, their storage, transfer, and utilization in space environments are fundamentally constrained by heat ingress from external environment, phase-change boiloff loss, and complex two-phase flow dynamics under reduced gravity and microgravity. This paper outlines the importance of cryogenic thermal-fluid management (TFM), identifies the governing physical processes, and presents key system elements required for reliable long-duration propellant storage and transfer. Particular emphasis is placed on Zero-Boil-Off (ZBO) technologies, which are essential for enabling in-space refueling, propellant depots, and nuclear thermal propulsion missions.

Keywords: Cryogenic propellant; Thermal-fluid management; Multilayer insulation; Cryocooler; Helium subsurface pressurization; Zero-boil-off (ZBO); Microgravity

1. Introduction

Cryogenic systems play a critical role in future human space missions beyond Low Earth Orbit (LEO). They are integral to chemical and nuclear propulsion systems, lander ascent and descent stages, and propellant depots, all of which rely on long term storage and transfer of propellants. Despite their superior performance compared to storable propellants, cryogenic propellants have a low boiling point, so designing and optimizing in-space cryogenic propellant systems requires knowledge of a variety of gravity-dependent two-phase flow, heat and mass transfer mechanisms.

The use of cryogenic propellants enables high specific impulse and efficient propulsion for both chemical engines and nuclear thermal propulsion (NTP) systems. Liquid hydrogen, in particular, is indispensable for NTP due to its dual role as propellant and reactor coolant. However, its low boiling point (~20 K) and high latent heat sensitivity make it extremely susceptible to boil-off loss under even small parasitic heat loads.

Cryogenic TFM encompasses the control of heat transfer, phase distribution, pressure, and fluid transport within storage, transfer, and feed systems. For long-duration missions, such as cislunar infrastructure and Mars transit, passive storage approaches are insufficient. Instead, integrated thermal-fluid systems—often incorporating active cooling by helium subsurface injection—are required to maintain propellant in a usable state over extended time periods.

2. Governing Thermal-Fluid Transport Challenges

2.1 Heat Leak and Boil-Off

The total heat ingress into a cryogenic tank can be expressed as the sum of radiative, conductive, and parasitic contributions:

$$\dot{Q}_{total} = \dot{Q}_{rad} + \dot{Q}_{cond} + \dot{Q}_{parasitic}$$

Even with state-of-the-art multilayer insulation (MLI), residual heat fluxes on the order of 0.1–1.0 W/m^2 are typical in space environments. For LH_2, this can result in significant vapor generation due to its extremely low boiling point and small latent heat of vaporization per unit density.
Boil-off mass rate is approximately:

$$\dot{m}_{boil} = \frac{\dot{Q}_{total}}{h_{fg}}$$

where h_{fg} is the latent heat of vaporization. Over mission durations of months, this leads to unacceptable propellant loss without mitigation.

2.2 Two-Phase Flow Behavior in Microgravity

In microgravity, buoyancy-driven phase separation is negligible, and fluid configuration is governed by capillary forces and wetting behavior. This leads to:

- Uncertain liquid-vapor interface positioning
- Stratification dominated by surface tension
- Increased likelihood of vapor ingestion during outflow

These effects complicate both storage, transfer, and engine feed, requiring capillary-based propellant management devices (PMDs).

2.3 Thermodynamic State Control

Cryogenic propellants may exist in subcooled, saturated, or two-phase states. Maintaining a controlled thermodynamic condition is essential for:

- Preventing cavitation in turbopumps
- Ensuring stable reactor cooling in NTP
- Enabling predictable pressurization behavior

3. Elements of Cryogenic Thermal-Fluid Management

3.1 Passive Thermal Control

- Multilayer insulation (MLI) to reduce conductive and radiative heat transfer
- Low-conductivity structural supports
- Vapor-cooled shields (VCS) to intercept heat

These systems reduce, but do not eliminate, heat leak.

3.2 Active Thermal Control and Zero-Boil-Off (ZBO) Systems

ZBO systems eliminate net propellant loss by actively removing incoming heat. The fundamental requirement for ZBO is:

$$\dot{Q}_{cooling} \geq \dot{Q}_{total}$$

where $\dot{Q}_{cooling}$ is the cooling capacity of the helium subsurface injection cooling, cryocooler or refrigeration system.

ZBO Architectures

1. **Direct Tank Cooling (Broad Area Cooling)**
    - Cryocoolers are thermally coupled to the tank wall
    - Heat is intercepted before reaching the bulk propellant
    - Reduces overall tank temperature gradients
2. **Internal Heat Exchangers**
    - Cooling loops or cold fingers immersed in the liquid
    - Promote bulk fluid cooling and destratification
    - Particularly useful for LH_2 due to high thermal stratification sensitivity
3. **Vapor Recondensation Systems**
    - Boil-off vapor is captured, routed through a cryocooler, and recondensed
    - Returned to the tank, maintaining mass balance
    - Often integrated with tank pressure control
4. **Helium subsurface pressurization (HSP) systems**
    - Warm helium gas is injected through orifices in the form of bubbles into liquid
    - Liquid evaporation inside bubbles cools down liquid propellant
    - Bubbles of vapor-gas mixture serve to pressurization purposes

ZBO Performance Considerations

- **Coefficient of Performance (COP):** Cryocoolers operating at 20 K have very low COP, leading to high electrical power demand
- **System Mass Trade-offs:** Added mass of cryocoolers, radiators, and power systems must be balanced against propellant savings. HSP small amounts of liquid consumed also must be balanced by boil-off losses.
- **Thermal Stability:** Avoidance of localized freezing or thermal oscillations
- **Scalability:** Large tanks (e.g., depot-scale) require distributed cooling architectures

For LH_2 systems, ZBO is particularly critical due to its high boil-off rate relative to denser cryogens like LOX or LCH_4.

3.3 Pressure and Vapor Management

Pressure control is achieved through:

- Autogenous pressurization (using warmed propellant vapor)
- Helium subsurface injection systems
- Controlled venting or recondensation

In ZBO systems, pressure control is tightly coupled with vapor recondensation, enabling closed-loop operation without mass loss.

3.4 Fluid Acquisition and Transfer

In microgravity:

- Capillary PMDs ensure liquid positioning at tank outlets
- Screen-channel and vane systems guide liquid flow
- Transfer operations require containing wall chilldown to prevent flash vaporization

ZBO systems can significantly reduce transfer losses by maintaining subcooled conditions prior to transfer.

3.5 Coupled Thermal-Fluid Interactions

Thermal gradients induce fluid motion (thermocapillary convection), which in turn affects heat transfer and phase distribution. Accurate modeling requires coupling:

- Energy equation
- Momentum equation (low-gravity regime)
- Interface tracking (e.g., Volume-of-Fluid methods)

4. Relevance to Chemical and Nuclear Propulsion

In chemical propulsion systems, reliable engines start and restart depend on delivering vapor-free propellant at controlled conditions. ZBO enables long-duration storage for reusable stages and orbital depots, directly supporting architectures such as in-space refueling. For nuclear thermal propulsion, cryogenic TFM is even more critical. Liquid hydrogen must:

- Enter the reactor in a controlled phase
- Efficiently absorb heat without premature phase change
- Maintain stable flow under high heat flux conditions

ZBO systems ensure that LH_2 remains in optimal thermodynamic condition prior to reactor entry, enhancing both performance and safety margins.

5. Lunar Orbital Depots: The "Gas Station" in Space

A lunar depot (like those envisioned for the Gateway or private propellant hubs) serves as a long-term storage facility. The primary challenge here is **Environmental Thermal Stability** over years of operation.

- **Continuous Zero-Boiloff (ZBO):** Because the depot must maintain its mass for multiple arriving and departing vessels, active cryocoolers are non-negotiable. The power budget for these coolers is a major design constraint, often requiring large solar arrays to drive the Reverse-Brayton cycles needed to lift heat at 20 K.
- **Propellant Transfer & Refueling:** This is arguably the most complex fluid task. Moving from a tanker to the depot in microgravity requires precise pressure control to avoid "geysering" or flash evaporation. It also involves advanced **Liquid Acquisition Devices (LADs, one type of PMDs)** that use surface tension to ensure only liquid flows through the transfer lines, preventing gas ingestion into the receiving tank.
- **Thermal Shadowing:** Strategies often involve orienting the depot so that the sunshield always faces the Sun, keeping the tanks in a permanent "thermal shadow" to minimize the load on the active cooling systems.

6. Mars Transit: The Long-Haul Challenge

For a Mass transit, specifically one utilizing **Nuclear Thermal Propulsion (NTP)**, the focus shifts to **High-Flux Transients and Mass Efficiency.**

- **Radiation-Induced Heating:** Unlike a depot, a nuclear-powered Mars vehicle faces internal heat generation. Neutrons and gammas from the reactor core can penetrate the propellant tanks, heating the propellants from the inside out. This requires "shadow shields" and potentially internal cooling loops to prevent the bulk liquid from reaching its critical point during long burns.
- **Mass-to-Power Ratio:** Every kilogram of cooling equipment is a kilogram of lost payload. For a 6-to-9-month transit, engineers must balance the mass of thick MLI (passive) against the mass of a powerful cryocooler (active). Often, a "hybrid" approach is used: passive

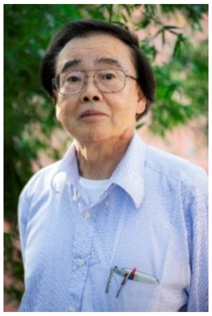
insulation handles the majority of the load, while a small active system mops up the remaining heat leak to ensure the tanks are full for the Mars Arrival Burn.

- **Startup/Shutdown Cycles:** NTP engines undergo extreme temperature swings—from 20 K propellant to 2,500+ K reactor temperatures in seconds. Managing the thermal-fluid "shock" to the system during these transients is a major area of current research, involving complex numerical simulations of bubble dynamics and phase change.

7. Conclusion

Cryogenic propellant thermal-fluid management is the "mission-enabling technology" for the next era of space missions and exploration. While passive methods can reduce heat leak, they are insufficient for long-duration missions. Active Zero-Boil-Off systems, enabled by cryocoolers, HSP, and integrated thermal architectures, provide a viable path toward indefinite propellant storage without loss. Whether fueling a chemical ascent vehicle or a nuclear-powered interplanetary cruiser, the mastery of these thermal-fluid management elements remains the gatekeeper to the stars.

Future developments must focus on improving cryocooler efficiency, HSP performance, reducing system mass, and advancing predictive models for microgravity two-phase flow simulations. These advances will be essential for enabling sustainable lunar operations, Mars exploration, and nuclear propulsion systems.



Dr. Jacob Nan-Chu Chung is the Andrew H. Hines, Jr./Progress Energy Eminent Scholar Chair Professor at the University of Florida. He joined the University of Florida in 1998 after 19 years on the faculty at Washington State University. Dr. Chung holds both B.S. and M.S. degrees in Nuclear Engineering and had spent 6 years working as a nuclear reactor safety engineer in the industry before receiving his Ph.D. in Mechanical Engineering from the University of Pennsylvania in 1979. Dr. Chung's research activities have been in the general areas of fluid mechanics and heat transfer. Dr. Chung is a co-author for a book entitled "Transport Phenomena with Drops and Bubbles". He has authored and co-authored over 230 archival journal papers and received the College of Engineering Research Excellence Award in 1988 at Washington State University. He was awarded the University of Florida, Herbert Wertheim College of Engineering, Doctoral Dissertation Advisor/Mentoring Award in 2008. He also received the 2014 ASME Heat Transfer Memorial award. Recently, he was awarded the "2023 Exceptional Public Service Medal" by NASA for his pioneering contribution to space cryogenic propellant thermal management. Dr. Chung has served as a technical consultant to the Battelle Pacific Northwest National Laboratory and the Hewlett-Packard Corporation. Dr. Chung is a Fellow of the American Society of Mechanical Engineers.