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Open problems in cryogenic propellant Systems for Space Launch Vehicles: a systematic review of technical gaps and evidence-based solution pathways

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ABSTRACT

Cryogenic propellant systems remain a key limitation in the performance, reliability, and reusability of modern launch vehicles, despite advances in propulsion technologies. This review analyzes research (2016–2026) on LOX/LH_2 and LOX/LCH_4 systems, focusing on storage, pressurization, chilldown, valves, turbopumps, and sensing, using a systematic qualitative approach. Eight main challenges are identified: boil-off and thermal stratification; transient fill and chilldown behavior; pressure-control instability and autogenous pressurization; cavitation; leakage, especially with hydrogen; sloshing and vehicle coupling; limited sensing and diagnostics; and durability of lightweight tanks. Proposed solutions include zero-boil-off systems, digital twins, improved pressurization, better thermal conditioning, distributed sensing, and composite tanks. However, these remain insufficiently validated at the system level. The review concludes that future progress requires integrated approaches combining thermofluid physics, monitoring, operability, and reusability, rather than isolated subsystem optimization, as a priority for 2026–2035.

1. Introduction

High-performance launch vehicles remain inseparable from cryogenic propellants. In most heavy-lift and upper-stage architectures, liquid oxygen combined with liquid hydrogen still defines the highest-performance chemical option, while liquid oxygen/liquid methane is increasingly favored where operational simplicity, reusability, lower coking, and improved turnaround are prioritized. Yet the specific impulse benefits of cryogenic propellants come with severe systems-engineering penalties: ultra-low temperatures, large density differences, two-phase transients, material contraction, venting losses, leak sensitivity, difficult chilldown sequences, and uncertain ground-to-flight transitions. In practice, the “fuel system” of a launcher is not a single component but a tightly coupled cryogenic ecosystem including tanks, insulation, pressurization hardware, feed lines, chilldown procedures, recirculation loops, valves, seals, sensors, ground interfaces, and the inlet environment seen by the engine turbomachinery.

This review is motivated by a central observation: the limiting factor in next-generation launch systems is increasingly not the nominal engine cycle alone, but the reliability, controllability, and repeatability of the complete propellant management chain around it. Large launchers have repeatedly shown that hydrogen leakage, tanking anomalies, thermal conditioning issues, pressure-control transients, and ground-vehicle interface behavior can dominate countdown risk even when engines are mature [1]. In reusable launch systems, the challenge is sharper because the propellant subsystem must survive repeated cryogenic loading, unloading, thermal cycling, inspection, refurbishment, and rapid turnaround without accumulating hidden damage, leakage susceptibility, sensor drift, or loss of control margin. What was traditionally treated as “support hardware” has therefore become a first-order determinant of mission assurance, launch cadence, and life-cycle cost.

The literature of the past decade shows major progress, but also persistent fragmentation. Some studies focus on tank self-pressurization and vapor–liquid stratification, others on chilldown in complex channels, cryogenic valves, helium heat exchangers, composite tanks, fault detection, autogenous pressurization, or sloshing. These topics are often studied in isolation, under different gravity levels, different propellants, different fidelity assumptions, and different validation standards. This fragmentation is not only bibliographic; it reflects a deeper engineering difficulty. A solution that performs well at component level may lose value when integrated with vehicle architecture, engine-start logic, ground operations, abort scenarios, or reusability requirements. Recent

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