Cryogenic Fuel Aviation - Challenges and Opportunities

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NASA aeronautics goals include pioneering new technology to increase efficiency and reduce emissions from air travel. The feasibility of using of on-board cryogenic fuels systems in combination with fuel cells, high efficiency engines, and electric motors for high efficiency commercial transport aircraft is being examined at NASA in collaborations with external partners. Growing emphasis on next generation air transportation resulted in the development of strategic investigations into cryogenic fuels aviation, including roadmaps for maturing new technologies, needs to improve testing and manufacturing capabilities, and the requirements for establishing regulatory and certification standards. A NASA cross-organizational multidisciplinary project team is exploring new aircraft architectures, enabling materials, and the engineering challenges associated with cryogenic fuels for aircraft. The engineering challenges include high performance cryogenic, thermal management, and power/propulsion components and subsystems to tackle the challenging problem of development of commercially viable aircraft that would radically transform air transportation.

A growing emphasis on exploring air transportation based on cryogenic fuels such as hydrogen resulted in the development of strategic programs on cryogenic fuels aviation, including developing new capabilities at the airports, expansion of hydrogen infrastructure, and fuel cells manufacturing both in the US and EU [1-2]. The feasibility of using fuel cells and on-board cryogenic fuels such as liquid hydrogen (LH_2), liquid natural gas or methane (LNG), and ammonia (LNH_3) systems in combination with electric motors for zero emission commercial transport aircraft has been examined in the past by NASA [3-4], and in the aircraft industry [5-6]. Broadly defined, these investigations revealed a necessity to mature key technologies (research in advanced materials for cryogenic fuel handling and aviation fuel cell and thermal management systems, powertrain energy management and control architectures, development of modeling tools, advanced manufacturing methods and sensors), developing test facilities for subsystems and power train at all levels of assembly and scale, establishing approaches to airframe integration of relevant power/propulsion subsystems, and supporting formulation of safety regulations and standards [7].

Development of aviation propulsion based on cryogenic fuels presents a unique fundamental challenge that has not been addressed by space technology nor commercial ground transportation. The primary issues unique to aviation revolve around the challenging transition from space propulsion applications having short lives (1 - 20 hours) and very low occupancy (0 - 4 passengers) to commercial transport applications requiring much longer service lives (5,000 – 15,000 hours) and greater occupancy (80 – 250 passengers) departing at a higher take-off rate from commercial airports rather than isolated launch sites. Aviation systems will be required to safely operate in occupied vehicles that are used several times a day, yet not dissembled and manually inspected between each flight. Safety and certification requirements for airframes with large integrated cryogenic tanks need to be defined in partnership with the Federal Aviation Administration (FAA) to increase the likelihood of passenger survival in the event of a crash. Systems for detecting and mitigating fuel leakage would have to be automated and redundant beyond current baseline operational procedures for space systems. Mean times between failure (MTBF) suitable for practical aviation propulsion life cycles will have to be demonstrated through actual testing of brassboard and production systems, and they will be required to meet FAA safety and certification requirements no less stringent than those for current commercial aircraft. Safety standards for hydrogen systems remain fragmented and inconsistent across regions. High-pressure storage, such as 350- and 700-bar systems, is governed by varying standards (ISO, SAE, EU) that are not fully harmonized, creating interoperability challenges. Similarly, leak detection and mitigation are hindered by the lack of unified, validated performance standards for hydrogen sensors in diverse environments, including outdoor refueling stations and industrial facilities. Material compatibility also remains a concern, as current qualification standards do not comprehensively address low temperature embrittlement or hydrogen embrittlement in metals or degradation in composite materials. Fire and explosion protection adds another layer of complexity, since testing methods for ignition sources, flame propagation, and deflagration risks differ significantly across applications.

Other subjects that need to be addressed in combination with the above regulatory challenges are the development of an encompassing aircraft architecture and optimal system integration making the commercial exploitation of a novel aircraft concept viable, as well as the development of relevant safety regulations and certification standards for the aircraft and its major components [8]. These studies are focusing on hydrogen turbine engines, fuel cells, electric motors, and hybrid-electric cycles integrated with cryo-fuels using consistent metrics of aircraft efficiency and emission improvements. It is important to mature the technologies required in parallel to the aircraft architectures so that the two can feed each other improving the probability of integrated system success.

There are numerous technology challenges for aviation with cryogenic fuel storage systems and propulsion including development of cryo-fuel storage and handling, thermal management systems, cryogenic fuel combustion in turbine engines, and next generation scalable engines and fuel cells. Initial challenge includes variabilities in turbine engines and fuel cells considered for integration into commercial aviation propulsion, each with expansive unknowns [9]. Cryogenic tank design, manufacturing, insulation, and integration into airframes will be challenging because of the lower density of the fuel requiring larger tanks for equivalent field length metrics [8]. Liquid cryogenic fuels' maximum handling maximum temperature and density significantly diverge from baseline Jet A fuel (kerosene) at 182 °C and 807 kg/m3 with LNH_3 at -36.3 °C and 675 kg/m3, LNG at -160 °C and 424 kg/m3, and LH_2 at -253 °C and 71 kg/m3. Although hydrogen offers a much higher gravimetric energy density (LHV ≈ 120 MJ/kg) than jet fuel (LHV ≈ 43 MJ/kg), its low volumetric density requires bulky storage systems, posing substantial integration challenges for long-range, large aircraft. LH_2 low temperature, low density, low viscosity, low lubricity, small molecular size (harder to control leakage), wide flammability range (between 4% and 75% in air), and potential for diffusion into or reaction with other materials increases the challenge of the design of systems that can simultaneously accommodate all these characteristics for a long (and highly cyclic) design life, in a lightweight, volumetrically efficient form factor. While many of these attributes have been successfully dealt with in ground systems, where weight is not a primary driver, or in space flight systems, where cryogenic systems are typically designed for short life (< 1 hour) and a low number of thermal and pressure cycles, there are several identified technology gaps with respect to the specific characteristics needed in an aviation application, including the requirement of sufficient durability for thousands of cycles and hours.

Similar to the cryogenic systems, the state-of-the-art fuel cell technology is validated for automotive applications and is too heavy for aeronautics. Fuel cells for space applications operate on pure oxygen rather than air, are at low scale, and designed to operate over a limited number of cycles. The fuel cell technology for aeronautical applications requires extensive technology maturation and scale up that achieves high specific energy at the system level and will require significant long-term investments to develop the technology and integrate it into cryogenic fuel aircraft architecture. Fuel cell material durability and performance under variable loads and operational stresses (e.g., takeoff-shutdown cycling, throttle transients, climatic variations, and air pollution) require comprehensive investigation [10]. Combustion in turbine engines of various potential cryogenic fuels produces significant changes in performance, efficiency, stability, and emissions in comparison with current aviation fuels. Aerospace propulsion applications will require durable, reliable combustor designs and materials tailored for integrated systems to extract optimal performance [7].

In addition to that, fuel cell and to leaser extend cryogenic fuel burning engine propulsion requires durable, reliable heat exchanger structures, tailored for promising integrated systems to extract optimal performance. The commercial aeronautical environment also uniquely challenges thermal/cryo-compatible joints, linkages, actuators and heat exchanger interfaces with repetitive thermal cycles and cumulative durations orders of magnitude over that of space propulsion experience. Challenges associated with cryo-fuel leakage detection, containment, and utilization, including the development of sensors, will be critical hurdles, and essential for safe operation of commercial aircraft in commercial airports and airspace [11]. Lastly, and beyond the scope of the current paper, are significant issues such as aircraft safety, increased challenges for ground operations, aircraft inspection and maintenance (amount and accessibility) that all need to be considered up front.

Ultimately, the reliability, durability, and operational life of cryo-fuel propulsion systems for commercial aviation applications will hinge on the materials used in cryogenic tanks, components (such as valves and pumps), heat exchangers, turbine engines and fuel cell components [9]. Material performance under cryogenic conditions becomes a central engineering and safety concern. Unlike the space sector, aviation applications require materials that can sustain long-duration, repeated cycles over a much longer lifetime in a more complex operating environment. Based on an RFI that NASA compiled from approximately 30 industry and academia sources [12], the two highest material priorities are material characterization and compatibility with cryogenic fuels followed by development of novel composites and insulation materials.

The emerging cryogenic fuels industry has indicated to NASA that hardware reliability and component-level advancements and scale-up, availability of safety standards and operations, and hydrogen transport as the most substantial technological gaps [12]. Safety standards, operational considerations (i.e. refueling), and training curriculum also were mentioned by many respondents. Based on these responses, there is a clear correlation that procedural safety and workforce development are both viewed as critical for successful adoption of cryogenic fuels. Extensive thermal, fluidic, mechanical, and performance testing in relevant conditions that can be used for life modeling and prediction along with inspection interval trials, and management of the associated supply chains are required. Essential aspect of introduction of cryogenic fuels to aviation is through facilitating testing which is an expensive endeavor requiring a specially trained workforce and significant infrastructure investments. A development of large-scale cryogenic testing facility supporting the implementation of new materials and technologies for aeronautical applications would enable the development of operational procedures for airport operations, and also support the needs for the development of technologies for ground transportation applications [12]. These needs may include testing from small scales, for such items as material development and characterization, to testing at large scale as large as full aircraft. The lack of large-scale integrated test facility has been specifically referenced as a major impediment on multiple levels, from ability to test individual components to full systems, also connected to such related subjects as workforce education, safety standards and sensors [12]. The existing US-based test facilities are not centrally or conveniently located with respect to the majority of potential users.

Although a full transition to hydrogen fuel for aviation applications may not be realized for decades as the ground systems for producing, storing, and handling hydrogen for airports and other modes of transportation are not yet developed, an investment in cryogenic technologies suitable for commercial aviation needs to be made now to allow for integration into aircraft entering service in the 2050s. The resulting technologies would be applicable to LH_2 and other cryogenic fuels such as LNG, should an alternative to cryogenic hydrogen emerge as a more suitable alternative to fossil fuels. The new sensors, materials, engines and fuel cells developed for the purpose of making cryogenic fuels viable in commercial aviation would not only contribute to the safety and durability of cryogenic space systems but would also help to enable the use of renewable cryogenic fuels in other transportation and energy applications of the future.

NASA assembled a cross-organizational multidisciplinary project team combining a diverse set of skills including aircraft architecture modelling and optimization, advanced material science, and engineering of high performance cryogenic, thermal management and fuel cell systems components and subsystems to tackle the challenging problem of development of commercially viable aircraft that would radically transform air transportation. Our team is developing an integrated conceptual and experimental methodology to realize an aircraft design based on cryogenic fuels management, fuel cells, engines, advanced power management and distribution, and thermal management systems combined with an integrated aircraft concept of operations both during the flight and at the airports. The resulting analyses suggested the aircraft architecture options, sizes and layouts for the propulsion subsystem and cryogenic fuel tankage to verify the weight-scaling relationships for a medium-range aircraft carrying 100-200 passengers flying 1000 - 5000 km. Distributed electric propulsion and cryogenic systems were further analyzed, and more detailed study identified systems goals for a viable overall system weight for missions of various lengths. The developed aircraft architecture is being optimized by total specific energy density, specific power, size and mission profiles.

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