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Grand challenges in aerospace propulsion

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Introduction

Aerospace propulsion technologies are well established and commercialized for low-speed to supersonic air flight, payload launch to space, and missions within space. However, present aerospace propulsion systems have a number of shortcomings, including their environmental impact, performance, and mission capabilities, which represent grand challenges to the aerospace engineering research and development communities. These and other shortcomings will need to be addressed through fundamental and applied research that seeks to improve current technologies and develop understanding of the underlying physics, new engineering methods, and new aerospace propulsion concepts and technologies.

With increased public interest in aerospace engineering, resulting from the wide access to air travel and increased number of space launches per year, and the increased economic activity and opportunity for scientific discovery that these activities have provided, the field of aerospace propulsion has a bright future. The grand challenges that our field faces, described in part here, offer great opportunities for the current and future generation of researchers. The Energetics and Propulsion section of Frontiers in Aerospace Engineering looks forward to supporting and disseminating research that addresses the current and future challenges in aerospace propulsion and energetics.

Decarbonization of aeropropulsion

The aviation sector will be one of the most difficult sectors of the global economy to decarbonize, due to the high energy density and other advantageous characteristics of conventional hydrocarbon fuels for aviation, which made the original development in aeropropulsion systems and their advancement over the last century possible. Aviation accounts for 2.5% of global CO_2 emissions. Additionally, due to contrails and factors relating to emissions and flight at altitude, aviation results in 3.5% of the effective radiative forcing on the earth's surface (i.e., 3.5% of the warming) (Lee et al., 2021).

Over the last several decades, there has been a massive increase in greenhouse gas emissions from aviation, due to the decreasing cost of air transport. The decreasing cost of aviation has resulted from both the decreasing capital costs of aircraft, due to technological development and innovation, and decreased fuel consumption, due to improved aeropropulsion systems that have become more efficient with increasing gas turbine pressure ratios and turbofan bypass ratios. The increased availability and accessibility of aviation has resulted in a ten-fold increase in the annual CO_2 emissions from the aviation sector since 1950. While during that period, the CO_2 emissions per passenger mile have decreased by twenty-fold, owing to the improvements in aeropropulsion systems and aircraft design (Lee et al., 2021).

To decarbonize the aviation sector, ultimately the fuel or energy sources used for aeropropulsion will have to be decarbonized and supplied by non-fossil sustainable resources (Nelson and Reddy, 2018). In addition, new propulsion technologies may be required to utilize new fuels or energy sources and the continued improvement of existing aeropropulsion architectures for increased efficiency, stability, and other improved performance characteristics is necessary.

The development of sustainable jet fuels, that can be directly utilized in exiting and future gas turbine aeropropulsion engines, is a challenge that is the subject of current research efforts (Nelson and Reddy, 2018; Chiaramonti 2019). These fuels may include sustainable aviation fuels (SAF) synthesized from sustainable biological resources, such as crops, waste oils, algal oils, and others, provided that these feedstocks do not have massive land and water requirements (Holmatov et al., 2019), such as those required by many first-generation biofuels (e.g., corn ethanol). Synthetic biology offers promise for the sustainable production of hydrocarbon fuels with similar characteristics to conventional fossil-derived jet fuels (Scown and Keasling 2022.). Synthetic biology makes it is possible to engineer microorganisms that can process carbon feedstocks to generate fuels directly, with potentially lower input costs, land requirements, and faster than competing processes. Electrofuels, or e-fuels, also offer the potential for sustainable aviation fuels (Goldmann et al., 2018). Electrofuels are typically synthesized from hydrogen, formed by the electrolysis of water using a renewable electricity source (wind or solar), and a carbon source (e.g., biological carbon feedstock or CO_2 captured from an exhaust stream or the atmosphere). While electrofuel fuel production is energy intensive, massive amounts of renewable electricity, that may be available in decades to come, could make electrofuels viable for transportation applications that require high energy density fuels, such as aviation. The development of sustainable fuels that attempt to synthesize hydrocarbons that are in or similar to those in current fossil-derived jet fuels (i.e., SAFs, fuels derived using synthetic biology, and electrofuels) will require research developments in biology, chemistry, and chemical engineering. Additionally, aerospace and mechanical engineers will need to optimize aeropropulsion engines for these new fuels and consider new modes of engine operation for increased efficiency and other improved performance characteristics.

Non-hydrocarbon fuels that have received considerable attention for use in aeropropulsion applications include hydrogen (Hoelzen et al., 2021) and ammonia (Boretti and Castelletto 2022), both of which offer the potential for net-zero carbon emissions. Hydrogen can be generated from water via electrolysis, and be net-zero carbon provided the electricity source for electrolysis is renewable. Net-zero carbon (green) ammonia can be generated from hydrogen and nitrogen separated from air, using renewable electricity. For the utilization of hydrogen as an aviation fuel, several engineering challenges need to be addressed, including storage on aircraft (i.e., cryogenic or high pressure), handling and transport of hydrogen, and stable combustion in gas turbine engines. Of course, the wide-scale production of green hydrogen via electrolysis is a considerable engineering challenge in itself. Ammonia, like hydrogen is a gas at standard temperature and pressure conditions; however, ammonia may be easier to implement into aviation infrastructure than hydrogen, given its higher boiling point (−33°C versus −253°C for hydrogen). Many of the same engineering challenges exist for ammonia, including synthesis, storage, transport, handling, and combustion in engines. Additionally, a major concern with ammonia is its toxicity (exposure limit of 50 ppm for humans) and standards will be required to ensure that those involved in the fuel supply chain are not exposed.

In addition to decarbonizing aviation fuels, advances in gas turbine jet engines must also continue to be pursued. For example, extreme gas turbine pressure ratios may be possible in the future that result in supercritical or transcritical combustor conditions. Fuel injection, mixing, and combustion under supercritical conditions is still not well understood, presenting a research challenge that requires fundamental research as well as technological developments to enable and control supercritical combustion in aeropropulsion systems (Oefelein 2019). Another fundamental phenomenon that is worthy of continued fundamental and applied research is pressure gain combustion (Kailasanath 2020). Pressure gain combustion implemented in gas turbines or other aeropropulsion systems could allow for increased efficiencies of the order of 10%–20%.

The electrification of aeropropulsion is in its nascent stage (Bowman et al., 2018); at this point, electric propulsion has mostly only be implemented in the form of pure electric propulsors for low thrust systems (small aircraft and UAVs) (Pelz et al., 2021). Electrification, both in the form of pure electric and hybrid electric aeropropulsion systems (Finger et al., 2020), is an area that will be of significant importance to development of new aircraft technologies and concepts in the coming decades, representing a grand challenge in need of new research efforts. Topics that will need continued research efforts include the development and integration of high energy density batteries (or other energy storage elements, e.g., super capacitors) for aeropropulsion and the development and optimization of electric and hybrid electric propulsion systems for various aircraft configurations. Electric propulsion will also allow for the development of new distributed propulsion systems (De Vries et al., 2019) that will allow entirely new aircraft designs to be envisioned.

Hypersonic air-breathing propulsion

Significant research and development efforts are underway towards the development of hypersonic vehicles that rely on air-breathing supersonic-combustion RAMJET (SCRAMJET) engines (Choubey et al., 2019). The primary limiting phenomenon in these engines is combustion at supersonic conditions where the residence times are of the order 10^{-4}–10^{-3} s (Liu et al., 2020). Combustion in these systems is complex, analogous to lighting and holding a match in a hurricane. It can take place in a diffusive or premixed mode and involves extremely fast mixing processes and chemical reactions. Hence, the design of SCRAMJET and other high-speed propulsion systems is dependent on, and limited by, flame stabilization at extreme conditions (Huang et al., 2019; Liu et al., 2020). Given the limiting nature of combustion processes in high-speed propulsion systems, understanding the fundamental phenomena and developing innovative flame stabilization schemes represent important research challenges for the development of hypersonic air-breathing propulsion.

Space propulsion

The development of electric propulsion devices for satellite station keeping have seen rapid growth over the last several decades, including Hall, ion, and electrothermal thrusters. However, research challenges exist in the development of new electric propulsion concepts that improve specific impulse, efficiency, scalability, longevity, and reliability of these systems (Dale et al., 2020; Holste et al., 2020). Examples of electric propulsion concepts for space that are under research and development include electrospray arrays, radio frequency- or microwave-systems coupled with magnetic nozzles, pulsed inductive thrusters, magnetoplasmadynamic (MPD), and nuclear thermal (NT) propulsion systems, among others (O'Reilly et al., 2021). Research challenges for future electric space propulsion systems will address the need to improve the specific impulse and longevity of high-thrust systems and the efficiency and reliability of low-thrust systems (Dale et al., 2020).

Solid and liquid fuels and energetics for chemical propulsion for space launch, other space applications, and munitions have been continually developed for about a century; however, there are still significant research challenges in the development of new fuels/energetics with improved properties and reduced environmental impact. These include the development of solid propellants and solid hybrid propulsion fuels utilizing additives for increase regression rate (Pang et al., 2021). Solid energetic formulations that take advantage of nanomaterial features (Van der Heijden 2018), or are additively manufactured, may allow a new paradigm in fuel design (Fleck et al., 2020). Green monopropellants for space propulsion can offer reduced environmental impact and address safety concerns, an important challenge that is being addressed (Nosseir et al., 2021). In addition, space launch propulsion systems are under development by SpaceX (Raptor), Blue Origin (BE-4), and others that use liquid methane fuel (Neill et al., 2009; Boué et al., 2018) rather than liquid RP fuels, indicating that further innovation in conventional liquid-propellant space launch systems is coming in the near future.

Computational modeling and design

Over the last several decades, computational methods for analysis and design of propulsion systems have been widely adopted by the commercial sector for the rapid development of aeropropulsion and space propulsion engines (Spalart and Venkatakrishnan 2016). These tools, primarily based on computational fluid dynamics (CFD), have resulted in tremendous cost reductions, improved performance, and rapid engineering design cycles. Today, CFD analysis for all parts of aero and space propulsion systems is possible to various degrees, using Reynolds Averaged Naiver Stokes (RANS), Large Eddy Simulation (LES), and hybrid turbulence modeling methods and submodels and/or simplifications for chemistry (e.g., flamlets) and other complicating physics. As computing power continues to expand, grand challenges towards the development of the next-generation computational modeling and design tools for aero and space propulsion include the greater implementation of LES models, towards full gas turbine jet engine transient modeling with LES (Anand et al., 2021). Additionally, the continued development of direct numerical simulation (DNS) for special use cases (e.g., combustion) is a challenge worth pursing (Gruber et al., 2021), such that source terms in sub-grid models used of engine component analysis and design can be better approximated. Developments in artificial intelligence and machine learning (AI/ML) should also be viewed as an opportunity to adopt an integrate novel data and AI/ML approaches to classical physics-based simulations such that those simulations can be accelerated and used for design optimization (Vinuesa and Brunton 2022).

Concluding remarks

The field of aerospace propulsion has a bright future, as the demand for air and space transport continues to expand. As highlighted here, there are several important scientific and technological challenges that will require focused research efforts for decades to come. The Energetics and Propulsion section within Frontiers in Aerospace Engineering seeks to advance research and development in the areas of air and space propulsion, power, energy, fuels, and energetics by publishing high-quality contributions in these areas that addresses challenges at the forefront of aerospace engineering.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Anand, M. S., Medic, G., Paliath, U., Suder, K. L., Malik, M. R., and Laskowski, G. M. (2021). "Vision 2030 aircraft propulsion grand challenge problem: Full-engine CFD simulations with high geometric fidelity and physics accuracy," in *AIAA scitech 2021 forum*, 0956.

Boretti, A., and Castelletto, S. (2022). NH3 prospects in combustion engines and fuel cells for commercial aviation by 2030. *ACS Energy Lett.* 7, 2557–2564. doi:10.1021/acsenergylett.2c00994

Boué, Y., Vinet, P., Magniant, S., Motomura, T., Blasi, R., and Dutheil, J. P. (2018). LOX/methane reusable rocket propulsion at reach with large scale demonstrators tested. *Acta Astronaut.* 152, 542–556. doi:10.1016/j.actaastro.2018.06.018

Bowman, C. L., Felder, J. L., and Marien, T. V. (2018). "Turbo-and hybrid-electrified aircraft propulsion concepts for commercial transport," in *2018 AIAA/IEEE electric aircraft technologies symposium (EATS)* (IEEE), 1–8.

Chiaramonti, D. (2019). Sustainable aviation fuels: The challenge of decarbonization. *Energy Procedia* 158, 1202–1207. doi:10.1016/j.egypro.2019.01.308

Choubey, G., Devarajan, Y., Huang, W., Mehar, K., Tiwari, M., and Pandey, K. M. (2019). Recent advances in cavity-based scramjet engine-a brief review. *Int. J. Hydrogen Energy* 44 (26), 13895–13909. doi:10.1016/j.ijhydene.2019.04.003

Dale, E., Jorns, B., and Gallimore, A. (2020). Future directions for electric propulsion research. *Aerospace* 7 (9), 120. doi:10.3390/aerospace7090120

De Vries, R., Brown, M., and Vos, R. (2019). Preliminary sizing method for hybrid-electric distributed-propulsion aircraft. *J. Aircr.* 56 (6), 2172–2188. doi:10.2514/1.c035388

E. S. Nelson and D. R. Reddy (Editors) (2018). *Green aviation: Reduction of environmental impact through aircraft technology and alternative fuels* (London, United Kingdom: Taylor and Francis).

Finger, D. F., Braun, C., and Bil, C. (2020). Comparative assessment of parallel-hybrid-electric propulsion systems for four different aircraft. *J. Aircr.* 57 (5), 843–853. doi:10.2514/1.c035897

Fleck, T. J., Manship, T. D., Son, S. F., and Rhoads, J. F. (2020). The effect of process parameters on the structural energetic properties of additively manufactured reactive structures. *J. Eng. Mater. Technol.* 142 (4), 041004. doi:10.1115/1.4047037

Goldmann, A., Sauter, W., Oettinger, M., Kluge, T., Schröder, U., Seume, J. R., et al. (2018). A study on electrofuels in aviation. *Energies* 11 (2), 392. doi:10.3390/en11020392

Gruber, A., Bothien, M. R., Ciani, A., Aditya, K., Chen, J. H., and Williams, F. A. (2021). Direct Numerical Simulation of hydrogen combustion at auto-ignitive conditions: Ignition, stability and turbulent reaction-front velocity. *Combust. Flame* 229, 111385. doi:10.1016/j.combustflame.2021.02.031

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., and Hanke-Rauschenbach, R. (2021). Hydrogen-powered aviation and its reliance on green hydrogen infrastructure–review and research gaps. *Int. J. Hydrogen Energy* 47, 3108–3130. doi:10.1016/j.ijhydene.2021.10.239

Holmatov, B., Hoekstra, A. Y., and Krol, M. S. (2019). Land, water and carbon footprints of circular bioenergy production systems. *Renew. Sustain. Energy Rev.* 111, 224–235. doi:10.1016/j.rser.2019.04.085

Holste, K., Dietz, P., Scharmann, S., Keil, K., Henning, T., Zschätzsch, D., et al. (2020). Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer. *Rev. Sci. Instrum.* 91 (6), 061101. doi:10.1063/5.0010134

Huang, W., Du, Z. B., Yan, L., and Xia, Z. X. (2019). Supersonic mixing in airbreathing propulsion systems for hypersonic flights. *Prog. Aerosp. Sci.* 109, 100545. doi:10.1016/j.paerosci.2019.05.005

Kailasanath, K. (2020). Recent developments in the research on pressure-gain combustion devices. *Innovations Sustain. Energy Clean. Environ.* 1, 3–21. doi:10.1007/978-981-13-9012-8_1

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., et al. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* 244, 117834. doi:10.1016/j.atmosenv.2020.117834

Liu, Q., Baccarella, D., and Lee, T. (2020). Review of combustion stabilization for hypersonic airbreathing propulsion. *Prog. Aerosp. Sci.* 119, 100636. doi:10.1016/j.paerosci.2020.100636

Neill, T., Judd, D., Veith, E., and Rousar, D. (2009). Practical uses of liquid methane in rocket engine applications. *Acta Astronaut.* 65 (5-6), 696–705. doi:10.1016/j.actaastro.2009.01.052

Nosseir, A. E., Cervone, A., and Pasini, A. (2021). Review of state-of-the-art green monopropellants: For propulsion systems analysts and designers. *Aerospace* 8 (1), 20. doi:10.3390/aerospace8010020

Oefelein, J. C. (2019). "Advances in modeling supercritical fluid behavior and combustion in high-pressure propulsion systems," in *AIAA scitech 2019 forum*, 0634.

O'Reilly, D., Herdrich, G., and Kavanagh, D. F. (2021). Electric propulsion methods for small satellites: A review. *Aerospace* 8 (1), 22. doi:10.3390/aerospace8010022

Pang, W., Li, Y., DeLuca, L. T., Liang, D., Qin, Z., Liu, X., et al. (2021). Effect of metal nanopowders on the performance of solid rocket propellants: A review. *Nanomaterials* 11 (10), 2749. doi:10.3390/nano11102749

Pelz, P. F., Leise, P., and Meck, M. (2021). Sustainable aircraft design—a review on optimization methods for electric propulsion with derived optimal number of propulsors. *Prog. Aerosp. Sci.* 123, 100714. doi:10.1016/j.paerosci.2021.100714

Scown, C. D., and Keasling, J. D. (2022). Sustainable manufacturing with synthetic biology. *Nat. Biotechnol.* 40 (3), 304–307. doi:10.1038/s41587-022-01248-8

Spalart, P. R., and Venkatakrishnan, V. (2016). On the role and challenges of CFD in the aerospace industry. *Aeronaut. J.* 120 (1223), 209–232. doi:10.1017/aer.2015.10

Van der Heijden, A. E. D. M. (2018). Developments and challenges in the manufacturing, characterization and scale-up of energetic nanomaterials–A review. *Chem. Eng. J.* 350, 939–948. doi:10.1016/j.cej.2018.06.051

Vinuesa, R., and Brunton, S. L. (2022). Enhancing computational fluid dynamics with machine learning. *Nat. Comput. Sci.* 2 (6), 358–366. doi:10.1038/s43588-022-00264-7