Hydrogen-powered flight

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As the Nation moves towards a hydrogen economy the shape of aviation will change dramatically. To accommodate a switch to hydrogen the aircraft designs, propulsion, and power systems will look much different than the systems of today. Hydrogen will enable a number of new aircraft capabilities from high altitude long endurance remotely operated aircraft (HALE ROA) that will fly weeks to months without refueling to clean, zero emissions transport aircraft. Design and development of new hydrogen powered aircraft have a number of challenges which must be addressed before an operational system can become a reality.

While the switch to hydrogen will be most outwardly noticeable in the aircraft designs of the future, other significant changes will be occurring in the environment. A switch to hydrogen for aircraft will completely eliminate harmful greenhouse gases such as carbon monoxide (CO), carbon dioxide (CO_2), sulfur oxides (SOx), unburnt hydrocarbons and smoke. While these aircraft emissions are a small percentage of the amount produced on a daily basis, their placement in the upper atmosphere make them particularly harmful.

Another troublesome gaseous emission from aircraft is nitrogen oxides (NOx) which contribute to ozone depletion in the upper atmosphere. Impacts from NOx reduction will not only be seen in the upper atmosphere, but also at airports where NOx has led to significant production of smog from ground ozone. Depending upon the propulsion system selected emission of nitrogen oxides (NOx) can be reduced dramatically or even eliminated altogether. Nitrogen oxide emissions are produced during the combustion process and are primarily a function of combustion temperature and residence time. The introduction of hydrogen to a gas turbine propulsion system will not eliminate NOx emissions; however the wide flammability range will make low NOx producing, lean burning systems feasible. A revolutionary approach to completely eliminating NOx would be to fly all electric aircraft powered by hydrogen – air fuel cells. The fuel cells systems would only produce water, which could be captured on board or released in the lower altitudes. Currently fuel cell systems do not have sufficient energy densities for use in large aircraft, but the long term potential of eliminating greenhouse gas emissions makes it an intriguing and important field of research.

Aircraft Configuration. Changes to aircraft design will be driven by the fundamental differences in properties between hydrocarbon based liquid fuels such as Jet-A and hydrogen. Hydrogen has nearly 2.8 times the energy per pound as Jet-A, however liquid hydrogen has 1/11 the density as Jet-A. Therefore, on an equivalent energy basis hydrogen has four times the volume as Jet-A. For aircraft, this translates into a significant shift in how fuel can be stored on the vehicle, resulting in dramatic changes to aircraft design. Many of today's current practices and design guidelines will need to be revisited. Unlike current aircraft, fuel will no longer be conveniently stored in wing tank bladders. The most efficient state to store hydrogen for flight application remains as a liquid. However, in the liquid state hydrogen is a cryogenic fluid and must be maintained at -36.7R (20.4K). Tank geometries to maintain a fluid in the cryogenic state are much more limited than with a fluid that can be stored at ambient conditions. To minimize structural weight, spherical and cylindrical shapes are the most efficient.

Over the years a number of design solutions have been put forward. Most of the ideas address the problem by incorporating various tank configurations in the fuselage. A number of concepts have been designed with hydrogen tanks located at locations in the fuselage including; separate tanks fore and aft, along the top running the length of the fuselage, and tank running tandem to the passenger compartment. In all cases, the result is an increase in fuselage diameter and surface area with a corresponding increase in aircraft drag. An example is shown in a NASA artists concept of a fore and aft tank configuration (figure 1).

Propulsion and Power. The most likely propulsion system to initiate a switch to hydrogen will be the gas turbine engine. However, any propulsion system based on the combustion of a fuel with air will not eliminate the production of NOx. In hydrocarbon systems, for flameholding and to avoid lean blow out the problem is enhanced by the need to burn near stoichiometric conditions, which produces a NOx rich hot zone. The problem can be resolved for hydrogen systems by taking advantage of the wide flammability range and running the combustion systems fuel lean. Equivalent turbine inlet temperatures can be reached without the required hot core, while maintaining flame holding and lean blowout. New fuel injector designs based on micromixing fundamentals can take advantage of the rapid diffusivity of hydrogen to produce quick, efficient mixing. Coupled with the faster kinetics of hydrogen, residence times can be reduced to limit NOx and shorten combustor lengths. Other keys to an efficient hydrogen system will be the effective use of hydrogen throughout the engine. Several possibilities include; inlet air cooling through the compressor, turbine blade cooling for higher combustion temperatures, combustor liner cooling, and nozzle heat exchangers to pre-heat the fuel. Integration of any or all of these concepts will require changes to existing engine designs.

Fuel cell powered aircraft are attractive as a long term solution to completely reducing aircraft emissions. However the current state-of-the-art would require a significant increase in fuel cell power density to enable electrically powered regional-/commuter- size aircraft and an even larger increase for large commercial passenger aircraft. In conjunction with the increases to fuel cell power density, power management technologies would need to be improved to supply megawatts of power throughout the aircraft. The more near term application for hydrogen powered electric aircraft is with the HALE ROA missions. The two most common missions are a 14 day mission with hydrogen-fed consumable fuel cell systems and a 6 month mission with a solar-regenerative hydrogen-oxygen fuel cell system. In a regenerative system, the fuel cell powers the aircraft during nighttime operations and the water produced is converted back to hydrogen and oxygen during the day when the vehicle is on solar power.

The two most promising fuel cell types for aircraft applications are the proton exchange membrane (PEM) fuel cell and the solid oxide fuel cell (SOFC). Each fuel cell type has advantages and disadvantages depending upon the application. For either system the key for future implementation on aircraft is to increase the specific power (kW/kg). PEM fuel cells are low-temperature devices ~175 F (80 C) offering quick startup times, but requiring pure gaseous hydrogen fuel. Increasing the PEM operating temperature will both improve tolerance to impurities and may improve the specific power for the system. PEM fuel cell stacks produce a significant amount of heat that is difficult to dissipate or produce additional work, resulting in the need for liquid cooling systems. Higher operating temperatures will increase the heat transfer temperature differential for improved heat dissipation, resulting system size and weight reductions. SOFCs operate at high temperatures, in the range 1292-1832 F (700-1000 C), and tolerate higher levels of impurities. Current research on SOFC is focused on planar designs due to the higher potential specific power. The solid oxide system could be used as a stand alone power source or, because of the high grade heat produced, combined with a turbine in a hybrid system to achieve high efficiencies. In contrast to PEM, SOFC operates with significantly more airflow through the stack which provides heat removal, eliminating the need and corresponding weight of a liquid cooling system. Both fuel cell types will require significant investments for incorporation into aircraft. Along with increases to the specific power, both operability and durability improvements will be required for flight applications.

One of the most noticeable changes with electric powered aircraft will be with the propulsor. The turbine engine will be replaced with an electric motor driving an advanced propeller or ducted fan (figure 2). The electric motors will have higher densities, resulting in a much smaller package in comparison to the turbine engine. The challenge for reaching high power density is obtaining high current density motor windings. The most promising candidate for large aircraft applications is a cryogenic synchronous motor with either high purity aluminum conductors or superconducting windings, such as Yttrium Barium Copper Oxide (YBCO) or Magnesium Diboride (MgB_2). The new materials will reduce motor weight partly by eliminating the heavy iron components commonly found in electric motors. In addition, improved cooling from the cryogenic hydrogen will lower the resistance (or eliminate it for superconductors) and increase the amount of current in the motor. For smaller aircraft either switched reluctance or permanent magnet motors that do not require cryogenic cooling may be acceptable choices. The keys will be designing high current density windings for switched reluctance machines or more advanced axial-gap permanent magnet machines with high-field magnet arrays. High motor shaft speeds will help improve motor power density however advanced gear boxes may be required to match the lower propulsor shaft speeds due to aerodynamic or structural limits for the propeller or fan. As a direct switch with the gas turbine the electric motor is a smaller package, but the equivalent fan diameter will grow in size to compensate for the loss of thrust from the hot gas core. Another option would be to the power aircraft from a number of smaller, distributed propulsors along the wings or fuselage.

Summary. As the Hydrogen Economy appears on the horizon, the introduction of hydrogen fuel into the aviation sector should be addressed. The elimination of emissions from all aspects of the transportation system will be a significant contributor to improving the quality of life on the planet.

Key Terms: Airplanes, Hydrogen, Cryogenic Tanks, Electric Motors, Gas Turbines, Fuel Cells, Emissions

FIGURES

CD-03-82427 Terry Condrich – NASA GRC/Indyne

Figure 1 - Conceptual 300 passenger hydrogen transport aircraft.

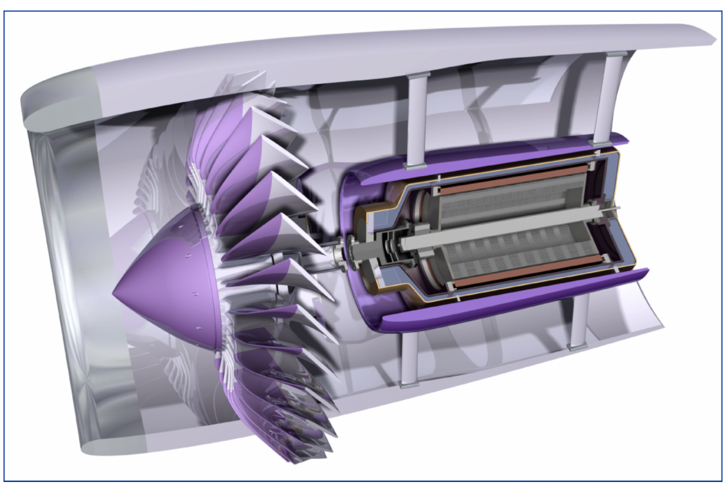

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Figure 2 – Conceptual cyrogenically cooled electric motor ducted fan.

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