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Exergetic sustainability improvement potentials of a hydrogen fuelled turbofan engine UAV by heating its fuel with exhaust gasses

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ABSTRACT

Exergetic sustainability parameters such as, exergy efficiency, waste exergy ratio, environmental effect factor and exergetic sustainability index were investigated for an UAV having a turbofan engine for the case its hydrogen fuel is heated by the exhaust gasses. Assessments include all the flight phases of the UAV taking place in the standard atmosphere with 60% relative humidity from 0 to 16 km altitudes. Physical hydrogen storages conditions are taken as some combinations of 20 K, 35 K, 80 K, 125 K and ambient temperatures and 1 bar, 25 bar, 50 bar, 100 bar, 200 bar, 350 bar and 700 bar pressures, including all the storage capacities from 0% to 100% by weight. Hydrogen is assumed to be delivered to the combustion chamber at ambient temperatures and just above the CC inlet pressures for fuel flow calculations. Maximum cumulative fuel saving potential was calculated as ~11% with liquid storage. Maximum instant exergetic efficiencies ranging ~0.3508 to ~0.3671, depending on the type of storage method, were obtained at the beginning of the cruise phase. Environmental effect factor and exergetic sustainability indexes present very close values having best cumulative values of 0.98 and 1.035 respectively for almost all.

Introduction

Owing to their numerous advantages over manned aircrafts, such as operability in adverse conditions for human pilots, design flexibilities and economical advantages, UAVs have been increasingly getting interest both for military and civil applications for a couple of decades. UAV market was the most dynamic growth sector of the world aerospace industry in the last decade and it is expected to proceed this trend in the next decade as well [1–4].

Even UAVs are smaller and use less fuel than an average aircraft in general, some UAVs can exceed 10 tonnes of weight and 36 h of operation. Therefore, their resource use and impact on the environment is comparable to those of average aircraft, deserving sustainability assessment as much as aircrafts.

There are many using and suggesting exergy analysis as a tool for energetic, economic and environmental assessment of activities or processes in various fields some of which can be found in Refs. [5–12] and some of its recent applications to the aerospace propulsion systems in Refs. [13–24].

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Hydrogen is a clean and renewable energy carrier having abundant resources on the earth, supporting almost all three pillars of sustainable development (environment, social and economic) either directly or indirectly.

Use of hydrogen as a fuel on aero-engines is not new and several success have been demonstrated since its first application on an experimental engine (HeS-1) derived from a turbo-jet engine and rig tested in 1937 by Hans von Ohain. Later, a number of countries experimented hydrogen fuel on aircrafts, as an alternative to tight oil supplies in the Second World War. About a decade later, the United States modified and flied Canberra bomber to fly on hydrogen fuel in 1956, with a complete secrecy to public until 1973. Although the interest then dimed time to time, mainly due to some practical considerations such as high cost and transformation challenges, it always conserved its strategic interest and researches almost never ceased. Soviet Union adapted a Tupolev to use hydrogen on one of its 3 engines and flew it successfully in 1988. A number of companies, mainly from Germany and Russia, collaborated to develop a hydrogen-fuelled airliner, called Cryoplane, in the early 1990s. The European Aerospace, Defence and Space company (EADS) is now leading a European consortium for studies on hydrogen propulsion systems, even there is not much evidence about its priority.

Main issues concerning use of hydrogen as a fuel for mobile applications are related to its storage such as weight and volume of storage systems, efficiency, fuelling-defueling rates, durability/operability and cost [25]. Among these, air vehicles are much more sensitive to weight and volume penalties (which may even abolish the application of a methodology) than the land or marine transportation vehicles due to power requirements to lift the weight and to overcome the drag forces during flight. Therefore, adequacy of a storage methodology for a mission duration, which is directly related to the storage capacity, must be examined first. Even current storage capacities by mass lies below 10%, all the storage capacities from 0% to 100% are examined for the considered UAV and its engine in this paper, aiming to include both the available flight time with a given capacity and the capacity needed for a given flight time. Beside, exergetic sustainability performances are evaluated for all storage capacities.

Background

Hydrogen has the highest energy density by mass (LHV ≅ 120 MJ/kg), but the lowest by volume among all the fuels (0.0108 MJ/L, ~0.033% that of kerosene) at ambient conditions as a gas. Therefore it has to be densified anyway to be reasonable even for stationary applications. Its densification involves either compression or its immobilization by cooling (including liquefaction) or bonding to some other materials or some combination of these. Storage in materials at ambient or above cryogenic temperatures (>150 K) generally impose some problems either as lesser storage densities due to weak H-material bonds or release difficulties due to strong bonds. Therefore, excluding some reactive hydrogen forming or reforming processes onboard, there almost always will be some heating requirements either to increase its heating values or to release it from the storage material. Owing to its high specific heat as well as its high liquid to gas and/or para to ortho conversion heats this involves a significant amount of heat up to about 4% of its LHV. Besides, heating it with the exhaust gasses will reduce the waste exergy and its adverse impacts on the environment. Therefore heating the hydrogen fuel with the exhaust gasses offers significant exergetic sustainability improvement potentials beside some practical benefits such as economy, longer flight times or applicability of lesser storage capacities.

Hydrogen exist in two isomeric forms as para and ortho hydrogen with their equilibrium fractions depending on temperature (Fig. 1). Para hydrogen is the more stable form having higher fractions at lower temperatures (Fig. 1) and having some heats of conversions higher than its latent heat of vaporization at temperatures below 125 K (Fig. 2). Hydrogen exhibits high specific heat as well even at very low temperatures in any of its forms (Fig. 3). Owing to its high specific heat, latent heat of vaporization and para to ortho conversion heats, hydrogen has a high specific heat capacity.

Even having heat exchangers in the exhaust channel may pose some problems such as pressure drops and turbulences decreasing linear speeds of the gasses hence the specific thrust, significant amount of fuel can be saved through some high effective heat exchangers (HX) placed on the hot gas flow as in Fig. 4. Besides, it is possible to regain the gas speeds and the original thrust by regulating the air flow post the heat exchangers, may be at some expense of weight and volume increments.

Literature review

Recently, production, storage and use of hydrogen as a fuel for mobile applications are on the focus of studies and researches demonstrating an immense number of studies in the literature. A rough survey of the literature related to two sets of key words given in Table 1, including topics at least two from the first set and of different nature and one from the second, revealed the studies given in Table 2.

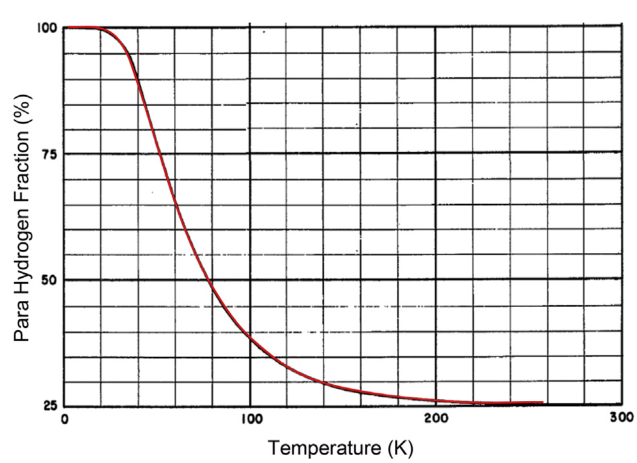

Fig. 1 – Variation of para hydrogen fractions with temperature [26].