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Engine-integrated solid oxide fuel cells for efficient electrical power generation on aircraft

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HIGHLIGHTS

- Integrated gas turbine/SOFC system for efficient in-flight electric generation.
- GT-SOFC system reduces fuel burn by several percent relative to generators.
- System capable of higher power levels than generators by avoiding TIT limit.
- Sensitivity analysis identified parameters important for optimization.
- Preliminary uncertainty estimate is below the predicted levels of improvement.

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ABSTRACT

This work investigates the use of engine-integrated catalytic partial oxidation (CPOx) reactors and solid oxide fuel cells (SOFCs) to reduce fuel burn in vehicles with large electrical loads like sensor-laden unmanned air vehicles. Thermodynamic models of SOFCs, CPOx reactors, and three gas turbine (GT) engine types (turbojet, combined exhaust turbofan, separate exhaust turbofan) are developed and checked against relevant data and source material. Fuel efficiency is increased by 4% and 8% in the 50 kW and 90 kW separate exhaust turbofan systems respectively at only modest cost in specific power (8% and 13% reductions respectively). Similar results are achieved in other engine types. An additional benefit of hybridization is the ability to provide more electric power (factors of 3 or more in some cases) than generator-based systems before encountering turbine inlet temperature limits. A sensitivity analysis shows that the most important parameters affecting the system's performance are operating voltage, percent fuel oxidation, and SOFC assembly air flows. Taken together, this study shows that it is possible to create a GT-SOFC hybrid where the GT mitigates balance of plant losses and the SOFC raises overall system efficiency. The result is a synergistic system with better overall performance than stand-alone components.

1. Introduction

1.1. Motivation

The electrical demands on air vehicles' power and energy systems are increasing substantially due to recent trends such as the replacement of hydraulic actuators and controls with electrical ones, growing sensor and telemetry payloads, and the introduction of new devices like in-flight entertainment systems (or even directed energy weapons). This trend is illustrated in Fig. 1 which compares estimates of electric power fraction (ζ) in various aircraft for which data are available [1]. The electric power fraction is defined as the ratio of electrical power demand to total power demand (propulsive and electrical) on the vehicle at cruise. Cruise propulsive power (or thrust) is estimated by reducing the sea level rated engine power (or thrust) by the cruise altitude density ratio (ρ_{cruise}/ρ_{SL}) and assuming a 60% throttle setting. While electric power fractions are relatively small ($1\% < \zeta < 2.5\%$) in typical commercial airliners, the Boeing 787 (a 'more electric aircraft') has an electric power fraction of approximately 4% and may be indicative of future trends. In the 787, electrically-powered cabin pressurization systems, pumps, and anti-icing systems [2] replace engine-driven ones. Future aircraft could have even higher electric power fractions ranging from $\zeta \approx$ 6% for aircraft with all-electric

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List of acronyms

APU	auxiliary power unit
BPR	bypass ratio
CEA	Chemical Equilibrium with Applications
CPOx	catalytic partial oxidation (reactor)
DGM	dusty gas model
GT	gas turbine
HALE	high altitude, long endurance
HPC	high pressure compressor
HPT	high pressure turbine
IR-SOFC	internally reforming solid oxide fuel cell
LPC	low pressure compressor
LPT	low pressure turbine
LSM	lanthanum strontium manganite
MEA	membrane electrode assembly
NPSS	Numerical Propulsion System Simulation
OPR	overall pressure ratio
RSS	root sum square
SOFC	solid oxide fuel cell
TIT	turbine inlet temperature
TSFC	thrust specific fuel consumption
UAV	unmanned air vehicle
YSZ	yttria stabilized zirconia

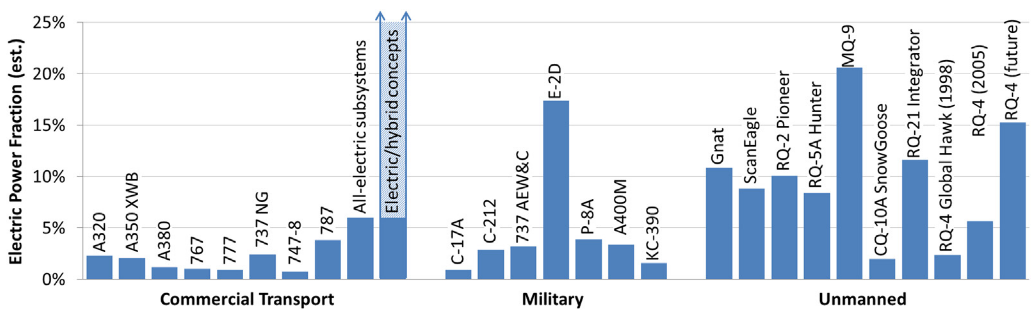

Fig. 1. Estimated electric power fractions in various commercial, military, and unmanned aircraft.

subsystems [3] up to $\zeta = 100\%$ for the large all-electric transport aircraft concepts envisioned by NASA [4]. Electric power fractions in existing manned military aircraft are comparable to those in commercial transport aircraft with the exception of the E-2D airborne early warning aircraft ($\zeta \approx 17\%$), notable for its large circular radar dome. Electric power fractions in unmanned air vehicles (UAVs) are substantially higher than in commercial aircraft, presumably because of large sensor and communications payloads. Electric loads will likely continue to increase as UAV technology matures: at its introduction in 1988, the RQ-4 Global Hawk was equipped with a 10 kW generator which was upgraded to 25 kW in 2005 [5] with another upgrade to 75 kW possible in the future [6]. Overall, the data indicate an upward trend in electrical power demand on aircraft. As this demand grows relative to propulsion, the efficiency of the electrical power generation process will have an increasingly important influence on vehicle range, endurance, and operational capability.

The standard methods for providing electrical power on turbine-powered aircraft are either mechanical generators driven by the high pressure shaft or smaller stand-alone turbine-based auxiliary power units (APUs) [1,5]. However, both are relatively inefficient because fuel passes through the Brayton cycle to produce mechanical power as an intermediate step before conversion to electrical power.

Fuel cells offer a direct and more efficient means of converting fuel to electrical power: up to 50–60% in systems without heat recovery cycles [7] vs. 20–40% for a typical gas turbine (GT) [8,9]. However, while fuel-cell based APUs are being studied [10,11], they are not in widespread use. The main reason is that the fuel cell reactor (or stack) requires a relatively complex system of pumps, blowers, sensors, controllers, and often fuel processors/reformers to deliver the appropriate reactants, maintain proper operating temperatures, and manage starting and shutdown transients. These additional components (referred to as 'balance of plant') add complexity, cost, and consume most of the efficiency advantage of the electrochemical approach over the heat engine. They also lower specific power substantially: The specific power of a stand-alone fuel cell is on the order of hundreds of W/kg [12] whereas that of modern heat engines is on the order of thousands of W/kg [13].

A potentially promising way to exploit fuel cells' high thermodynamic efficiency while minimizing balance of plant and specific power penalties is to integrate a catalytic partial oxidation (CPOx) reactor and solid oxide fuel cell (SOFC) into a gas turbine engine's flow path. An example of such an integration is presented in Fig. 2. Air enters the inlet and is pressurized by a compressor. The majority of the pressurized air passes directly to the burner/combustor where fuel is mixed in and burned. Bleed air from the compressor feeds the CPOx/SOFC and the SOFC exhaust discharges into the

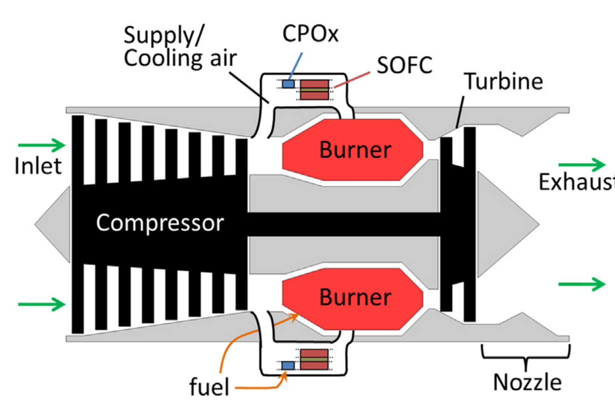

Fig. 2. Illustration of how CPOx/SOFC elements located in an annular duct around the engine could be integrated with a turbojet's flow path.