Solid Oxide Fuel Cell Combustor Gas Turbine Hybrid Power System for Commercial Electric Aircraft

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Abstract

Commercial aviation is a vital part of modern society. In 2018, commercial aviation was responsible for 2.4 percent of the total global carbon dioxide emissions and these numbers are expected to triple by 2050. This percentage seems relatively low, but if the commercial aviation industry was considered a country in the national carbon dioxide emission standings, it would rank sixth in the world. The addition of carbon neutral aviation provides a method to lower the carbon dioxide and greenhouse gas emissions caused by current methods of air travel. The proposed solution is to create an electrically powered aircraft that has a net zero carbon emission and can match the performance of current commercial aviation. A solid oxide fuel cell combustor gas turbine hybrid system (SOFCC-GT) is a viable option to provide an aircraft with enough power for full operation. SOFCs utilize an onboard hydrocarbon fuel and ambient air to produce electricity through electrochemical reactions and typically operate between 650°C – 850°C. The proposed SOFCC-GT will be capable of generating 24 MW of electrical power for the aircraft. The electrical power will be utilized by the propulsion, avionics, and all other electrical systems used in modern commercial aircraft. To validate the SOFCC-GT system, steady state and transient modeling will be used to simulate the system operation under various flight conditions. Pressurized testing of an SOFCC system will be completed and studied to evaluate the power densities generated by the SOFCs and to increase the fidelity of the system models.

Fuel Cell Background

Fuel cells are composed of 4 primary components: the anode (positive electrode), the cathode (negative electrode), the electrolyte, and the interconnections. Fuel cells use electrochemical reactions to convert the energy in hydrogen fuels to electrical energy. There are different types of fuel cells and each has their drawbacks and strengths. Solid oxide fuel cells are being investigates for their use in electric aircraft in this project. Below is a table of the five major fuel cell types.

	PEMFCs	AFCs	PAFCs	MCFCs	SOFCs
Temp. (°C)	80	65 – 220	150 – 220	650	600 – 900
Pressure (atm)	1 – 5	~	1 – 8	1 – 3	1 – 15
Efficiency (%)	40 – 50	40 – 50	40 – 50	45 – 55	50 – 60
P.D. (kW/kg)	0.5 – 2.5	0.15 – 0.4	0.15 – 0.3	0.1 – 0.3	0.25 – 0.5
Power (kW)	0.001 – 1000	1 – 100	50 – 1000	100 – 100K	10 – 100K
Electrolyte	Solid	Liquid	Liquid	Liquid	Solid
Catalyst	Pt	Pt	Pt	Ni	$CaTiO_3$
Fuel Source	H_2 (reform)	H_2 (pure)	H_2 (reform)	$H_2/CO/CH_4$	$H_2/CO/CH_4$
Oxidant	O_2/Air	O_2	O_2/Air	CO_2/O_2/Air	O_2/Air
Type	Small Utility	Aerospace	Small Utility	Utility	Utility

SOFCs operate at temperatures between 600°C – 1000°C, pressures between 1 and 15 atm, and have a power density of around 0.25 – 0.5 kW/kg. SOFCs can produce electrical power from a wide range of hydrocarbon fuels. The ability to operate at high temperatures, a wide range of pressures, and to use a wide range of fuels allow SOFCs to have a place in a Brayton cycle.

An SOFC produces electrical energy by taking advantage of the free electrons produced in the oxidation-reduction reaction between hydrogen and oxygen to form water. The below combined reaction and half reactions are an example electrochemical reaction that fuel cells use to generate electricity.

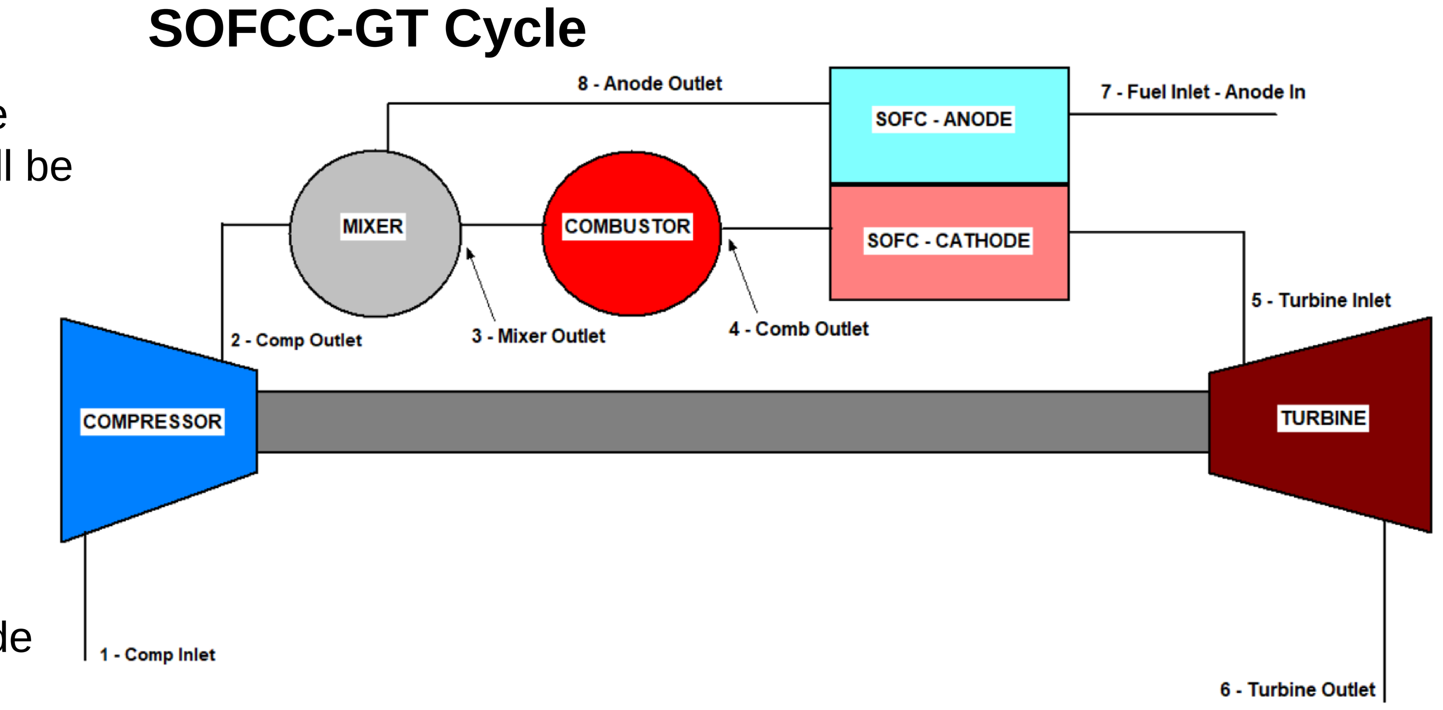
$$\text{Anode}: \quad H_2(g) + O^{2-} = H_2O(g) + 2e^-$$

$$\text{Cathode}: \quad 2e^- + \frac{1}{2}O_2(g) = O^{2-}$$

and the overall cell reaction becomes

$$H_2(g) + \frac{1}{2}O_2(g) = H_2O(g).$$

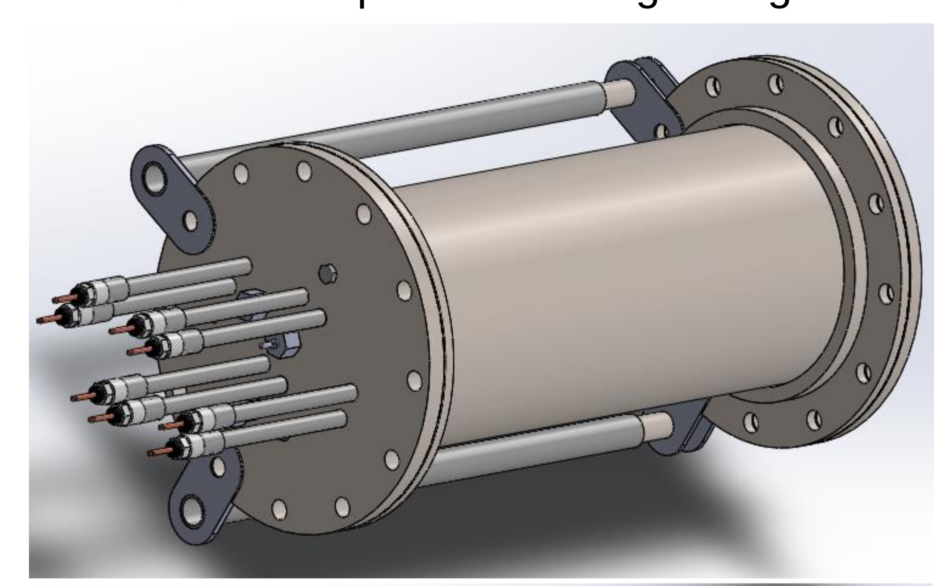
SOFCC-GT Cycle

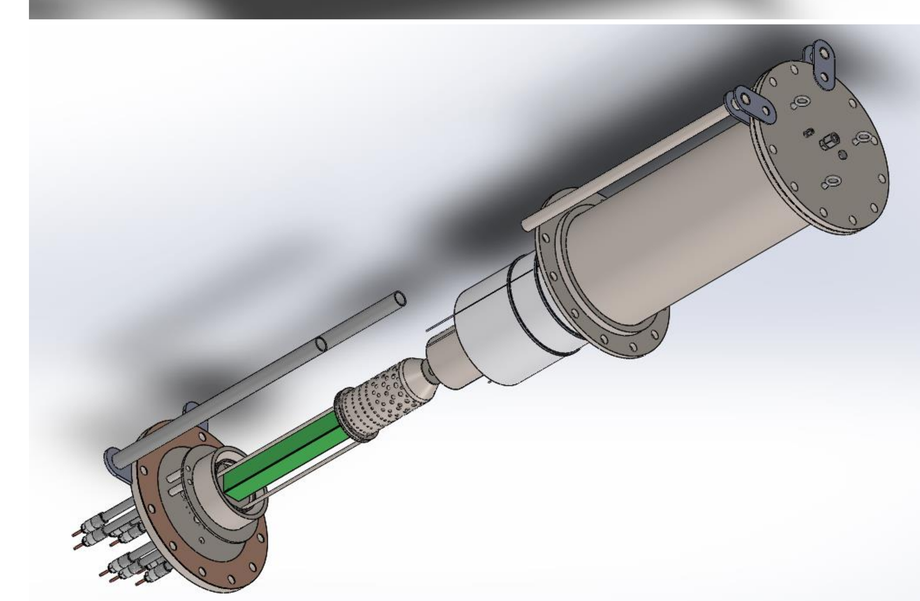


The SOFC combustor gas turbine hybrid cycle can be seen above. This cycle utilizes the pressurized air from the compressor and premixes/combusts this air with the onboard fuel that has already been passed through the anode. The compressor outlet temperature will vary between 145°C – 460°C based on altitude range of 1000ft - 35,000ft. The combustor allows for the cathode gas to be heated to the operating temperature of the SOFC. This cathode gas will then be used to heat up the SOFC stack within the range of 600°C to 900°C. This pressurized fuel cell off gas will then be sent to the turbine which will further generate electrical power. The anode fuel will be used to cool the electrical components of the aircraft thermal management system. This will include cryogenic electric motors used for the aircrafts propulsion, the avionics and aircraft control systems, the cabin, and any other component on the aircraft that needs to be cooled. This cooling will then heat up the fuel to close to the operating temperatures of the SOFC stack. The complete cycle will produce 24 MW of electricity. This power will be used for propulsion and aircraft control system. The electrical power generated will be stored in a battery back to allow for the system to be able to adapt to rapid load changes without quickly changing the operation of the SOFC stack.

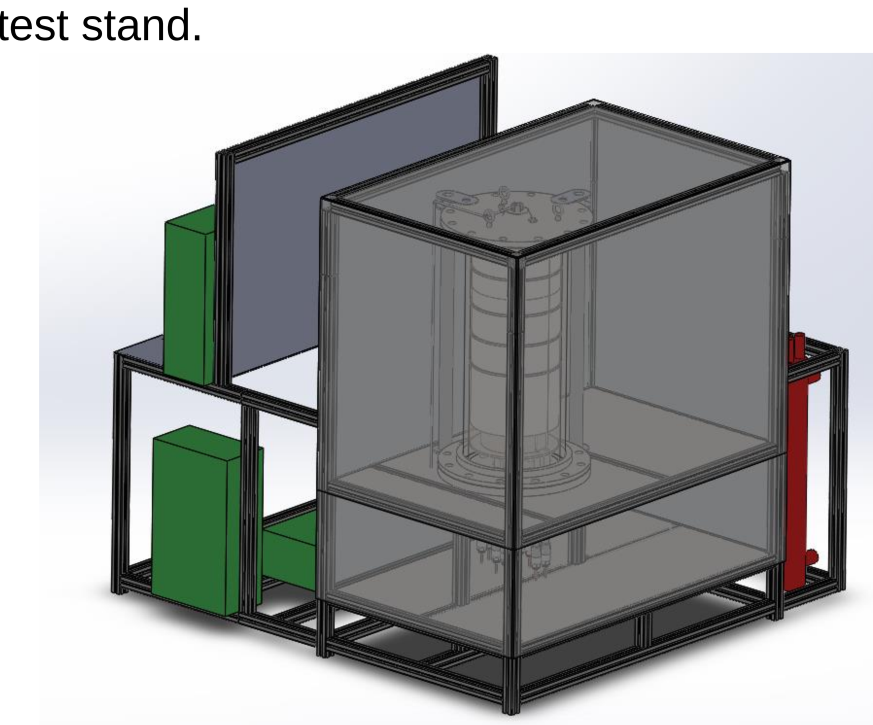
Development of Pressurized SOFC Test Stand

To develop a high temperature vessel capable of holding pressure the worst-case scenario of a fuel oxidizer mixture had to be examined. This worst-case scenario would involve a stoichiometric mixture of the fuel and oxidizer reactants which would create the largest amount of pressure change to the system. After determining the combustion temperature of a stoichiometric mixture of 2600 K for H_2 and 2300 K for CH_4. The largest pressure was determined to be 460 psi, which would occur at room temperature and at operating pressure (60 psi). The dimensions of the vessel were then designed using these values as maximum operating points. The vessel must also be kept above the auto ignition point of the fuel used to ensure there is no unwanted combustion of the fuel outside the vessel. Below is a figure depicting a pressure vessel capable of testing a single cell.





A Test stand structure to contain this vessel along with all of the control components, electronics, and gas plumbing was created. The vessel is surrounded in a nitrogen environment to ensure no combustion occurs inside the test stand enclosure. This structure allowed for the vessel to be oriented vertically to allow for the use of a crane to raise and lower the outer piping of the pressure vessel. The below figure displays the entire test stand.



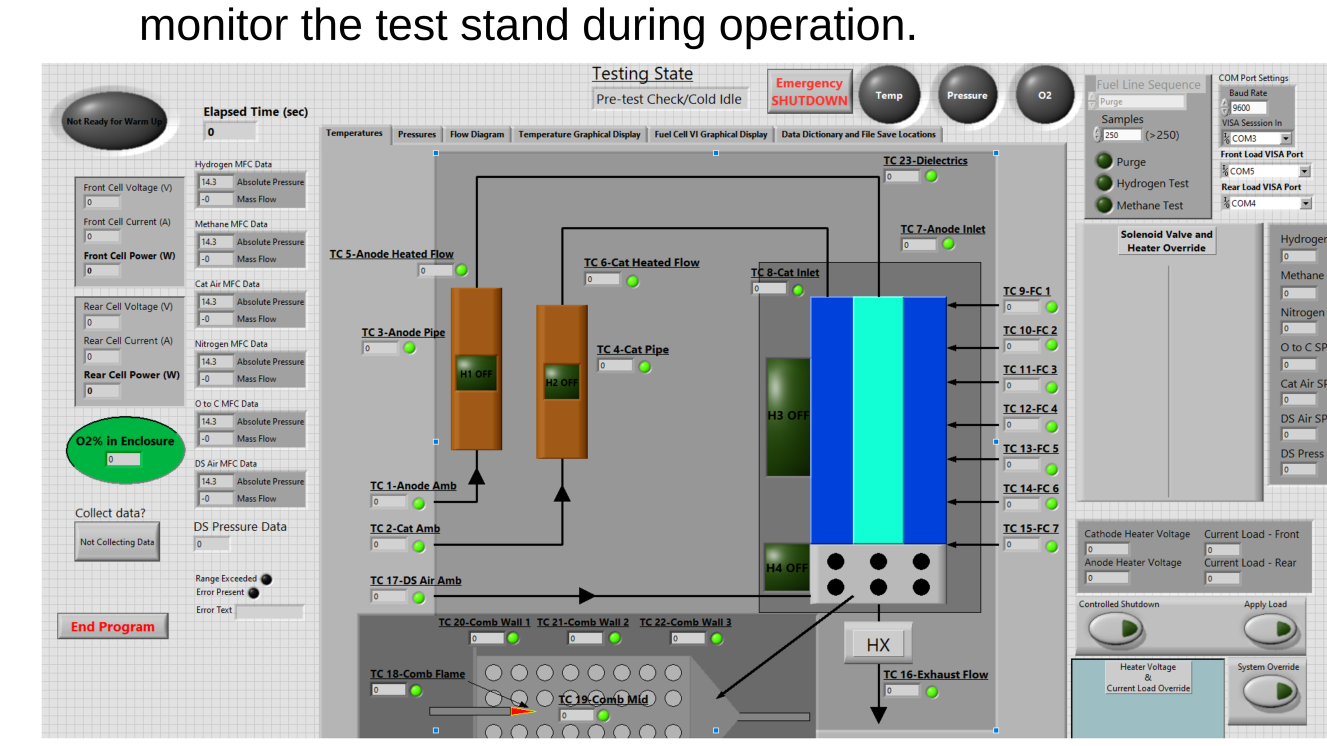
Gas Heat Exchangers and Heating Components

To emulate the conditions of operation in an electric aircraft, the fuel cell needs to be fed gases at the SOFC operating temperatures. The heating of the gases was decided to be done with induction heaters. Induction heaters operate using a copper coil that induces a magnetic field when current is ran through it. This magnetic field can then be utilized to heat ferrous materials inside the coil. Two induction heaters are used in the SOFC test stand, one heater to preheat the cathode gas, and one heater to preheat the anode gas. Inside each of the induction coils, a stainless steel, honeycomb style heat exchanger is used to efficiently transfer the heat of the metal to the flow. The heat exchanger design was determined experimentally along with some rough hand calculations to verify its effectiveness.

The fuel cell and combustion chamber are surrounded by a cylindrical resistive heater. This heater is utilized to maintain the combustion zone above the autoignition temperature of the fuel and is also used to maintain the fuel cell at the desired operating temperature.

Test Stand Control System - LabView

The testing process of the fuel cell requires a very controlled procedure. The temperatures, pressures, mass flow rates, and electrical loads of the system must be closely monitored and controlled to produce a successful test. LabView was the program of choice to complete this task. Several states of the testing process were determined to allow for various set points of the system to be reached and maintained and then allow for the system to move on or repeat various states. The system states are Cold Idle, System Warm Up, Steady Operation, Controlled Shutdown, and Emergency Shutdown. When previously determined temperatures, pressures, mass flows, and fuel cell powers have reached their setpoints, the system will automatically move between the desired testing states while recording the needed data. Below is the GUI used to monitor the test stand during operation.



Desired Testing Results

The desired results of the testing of the SOFCC system will be to verify the power densities of various SOFC sizes. The power density of the fuel cells will be evaluated at a large range of operation parameters. The system will be evaluated at a range of pressures, temperatures, fuel utilizations, and operation time. A standardized IV curve will be generated from each of these parameter varying tests to visualize the performance and overall operation of the SOFC.

Thanks to ARPA E – REEACH for supporting this project, also the support of my faculty advisor, Dr. Rory Roberts and his other student researchers.