

Explorations – The Journal of Undergraduate Research, Scholarship and Creativity at Wright State

Volume 1

Issue 1 *Summer Undergraduate Research, Scholarship and Creative Activities Issue 2012*

Article 10

2012

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Recommended Citation

Milliner, J., & Roberts, R. (2012). Analysis of Solid Oxide Fuel Cell-Gas-Turbine Hybrid System Technology for use in Aircraft, *Explorations – The Journal of Undergraduate Research, Scholarship and Creativity at Wright State*, 1 (1).

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August 2012

Analysis of Solid Oxide Fuel Cell-Gas-Turbine Hybrid System Technology for use in Aircraft

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Solid oxide fuel-cell-gas-turbine (SOFC/GT) hybrid systems are a technology that provides a more efficient source of energy for a variety of uses. One potential use is to provide more efficient energy to aircraft, which is the subject of this work. Potential applications to aircraft and results from a computer model of a SOFC/GT are presented here.

INTRODUCTION

As costs for fossil fuels increase and the desires to utilize energy with minimal environmental impact increase, so has the drive to produce more efficient power plants/engines for transportation and land based energy needs. Transportation is a major source of energy use and, correspondingly, pollution. A hybrid system or combined system uses more than one method of converting energy in order to produce an overall higher efficiency of energy conversion. One such hybrid system is the SOFC/GT. This system utilizes a solid oxide fuel cell (SOFC) and a gas turbine engine. The SOFC/GT system has applications for the aircraft industry due to the wide use of gas turbine engines in aircraft. This analysis points out some potential applications of such a hybrid system and involved the creation of a computer model to simulate an SOFC/GT.

SOFC

An SOFC is a type of fuel cell; a device which converts the chemical energy stored in a fuel to electricity via an electrochemical process. Fig. 1 illustrates the basic operation of a solid oxide fuel cell. Each cell of an SOFC consists of an anode and a cathode with an electrolyte in between. Air is supplied to the cathode side and fuel to the anode side. At the cathode, oxygen is reduced to oxygen ions. These ions diffuse through the electrolyte to the anode side where they electrochemically oxidize the fuel. The by-products of this reaction are electrons

which pass through a circuit to produce electricity and water (if the fuel used is hydrogen). Eq. 1 and Eq. 2 show the reactions that happen at the cathode and anode. The SOFC distinguishes itself among other fuel cell types by using a ceramic electrolyte, which reduces the cost of manufacturing. The use of ceramics means the SOFC must operate at high temperatures (600+ deg. C) and the products of the SOFC leave the device at this high temperature. It is the heat energy of these products that can be recaptured and utilized by a gas turbine engine.

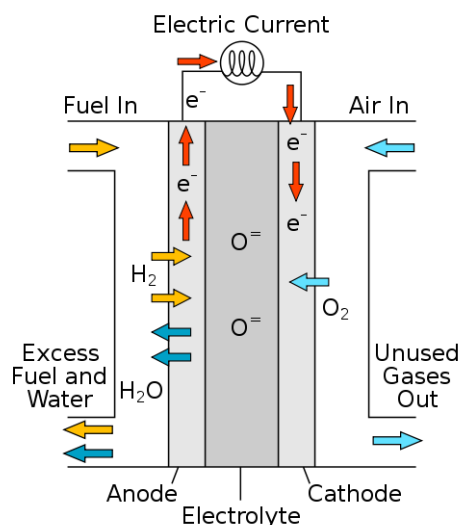


Fig. 1 SOFC Operation

Another benefit of the high temperature operation of an SOFC is that a wide variety of available fuel sources can be used, such as natural gas, and even gasoline or jet-fuel provided that these heavier fuels go through an external reformation process before entering the SOFC.

Cathode Reaction:

(1)

Anode Reaction:

+ (2)

GAS TURBINE

A gas turbine is a type of internal combustion engine; an engine that converts a fuel into mechanical energy through the use of the combustion process. Fig. 2 illustrates the basic operation of a gas turbine engine. A gas turbine draws in air from the atmosphere. This air is passed through a compressor where its pressure is greatly increased. The pressurized air then enters the combustion chamber where it is mixed with fuel and then combusted to produce a high temperature gas stream which passes through turbine blades before exiting the engine. The turbine blades extract mechanical energy from the gas flow and rotate a shaft which is connected to the compressor, allowing its operation.

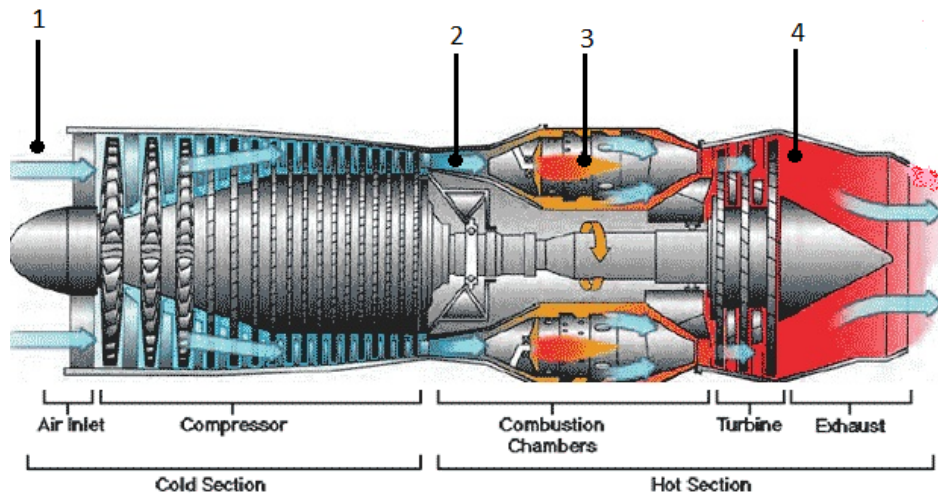


Fig. 2 Gas Turbine Operation

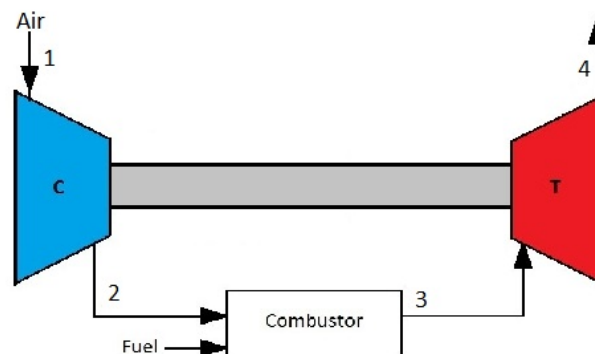


Fig. 3 Gas Turbine Diagram

THE SOFC/GT HYBRID SYSTEM

Fig. 4 shows the hybrid configuration. The hybrid system is configured by allowing the SOFC to receive air from the gas turbine compressor outlet. This forms what is known as a pressurized SOFC/GT system because the SOFC receives pressurized air. The high temperature exhausts of both the combustor and SOFC meet together to drive the turbine section of the gas turbine. The resulting hybrid system thus produces both mechanical and electrical energy. The aircraft industry is moving toward the more electric aircraft concept or MEA. (Santin, Traverso, & Massardo, 2008) This means future aircraft systems will be more reliant on electrical power thus boosting the power requirement of aircraft. Current aircraft use a generator to produce electrical energy which robs the main engines (gas turbines) of power. The use of an SOFC/GT would alleviate this problem by producing electrical energy without burdening the main engines. Alternatively, an SOFC could power an electric motor to help drive a propeller or rotor of an airplane or helicopter respectively. Both applications would reduce CO₂ emissions and boost fuel efficiency. Much development in SOFC and SOFC/GT technology, however, still needs to be conducted in order to effectively adopt these applications.

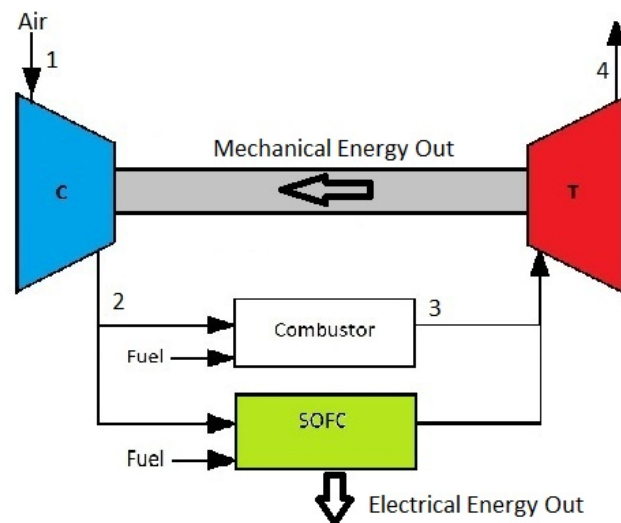


Fig. 4 SOFC/GT Diagram

SOFC/GT HYBRID SYSTEM MODEL

Using the matrix laboratory (MATLAB) programming language a simplified computer model was created in order to gain insight into the performance of the system. Basic equations from thermodynamics, and other resources were used to define this system in MATLAB and to calculate performance. The gas turbine was defined in MATLAB using the real Brayton thermodynamic cycle with air assumed as the working fluid. Input parameters for the gas turbine are properties of a selected gas turbine engine. For this model, input properties were taken from a Honeywell TPE-331 gas turbine engine, thus π_c , \dot{m}_{air} , P_{shaft} and TIT are known. The end goal is to be able to calculate the power output of the gas turbine so the enthalpy (h) at states 1, 2, 3 and 4 are needed. Sea level conditions are assumed for the initial state and so h_1 is known. h_2 is solved for using partial pressures and the following equation which yields P_{r2} .

$$P_{r2} = \pi_c P_{r1} \quad (3)$$

Since h_3 is defined by the selected TIT, it is known.

h_4 is found in a similar fashion to h_2 , with partial pressures using this slightly different equation.

$$P_{r4} = \frac{1}{\pi_c} P_{r3} \quad (4)$$

Using equations (5), (6), and (7) the power output of the gas turbine is calculated as well as the work requirement for the compressor and work output of the turbine.

$$W_c = \frac{h_{3,s} - h_2}{\eta_c} \quad (5)$$

$$W_t = \eta_t (h_3 - h_{4,s}) \quad (6)$$

$$P_{shaft} = \dot{m}_{air} (W_t - W_c) \quad (7)$$

Values of η_t and η_c were not provided for the engine so they were guessed to yield a P_{shaft} of 671 kW, which is the rated power of the TPE-331 engine. As a result, values of .7 were used for η_t and η_c , which are reasonable. For the SOFC a much simpler model was used due to time constraints. The electrical power produced by the SOFC was defined by the energy balance equation given below with an assumed η_{SOFC} of 50%.

$$P_{SOFC} = \eta_{SOFC} (P_f + P_{air} - P_{exh}) \quad (8)$$

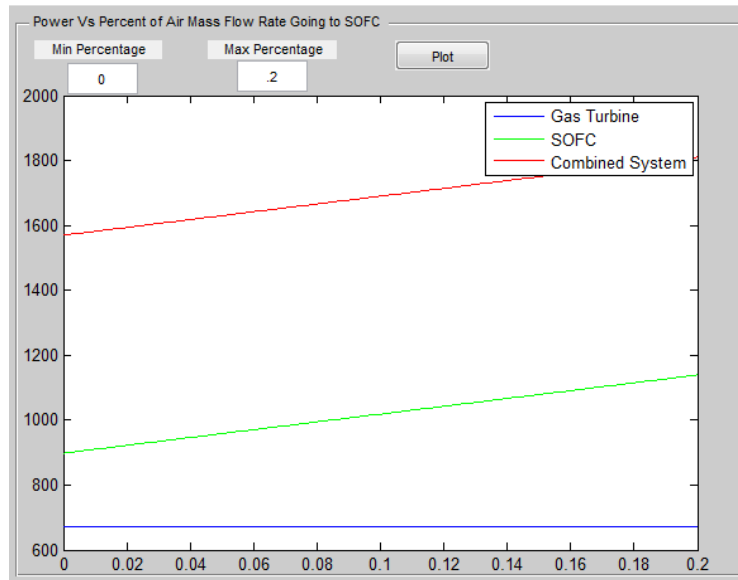


Fig. 4 SOFC/GT Power Output (kW) vs. r_{air}

RESULTS AND CONCLUSIONS

Fig.4 shows a plot from the MATLAB program where the power of the gas turbine, SOFC, and the combined system are plotted against the fraction of \dot{m}_{air} going to the SOFC (r_{air}). The increase in SOFC power with respect to r_{air} is as expected. The power for the gas turbine remains constant because it is independent of r_{air} . Looking at the combined power output of the system, the value is almost twice that of the SOFC alone and at least close to three times the power output or more of the gas turbine alone, showing the obvious advantages of such a hybrid system. It is important to remember however that this model has been simplified due to the assumption of air as the working fluid, when actually the gas mixture produced by combustion of fuel and air in the combustor as well as the gas mixture produced by the electrochemical process in the SOFC need to be accounted for. The simplified model of the SOFC also ignores some of the electrochemical reactions that occur to produce electrical power and thus a more in-depth SOFC model should be created. Addressing these simplifications would result in a more detailed and thus accurate model of the hybrid system and will be the nature of the work that will be conducted this coming fall. The creation of a dynamic model will also be attempted in the fall as well. Once a well developed model of the SOFC/GT is created the next step will be to analyze its performance in an aircraft subjected to variations in altitude and velocity. Sizing of an SOFC/GT system would also need to be accomplished, leading to the analysis in

regards to the effect of a hybrid system's weight and volume on an aircraft's dynamics and flight performance. The SOFC/GT has promising applications for aircraft. The realization of these applications will be dependent upon the outcome of future research and development with the SOFC/GT hybrid system.

NOMENCLATURE

h_i = enthalpy at state i (kJ/kg)
 h_{is} = isentropic enthalpy at state i (kJ/kg)
 h_{ia} = actual enthalpy at state i (kJ/kg)
 T_i = temperature at state i (K)
 P_{ri} = partial pressure at state i
 π_c = pressure ratio of gas turbine
 P_{shaft} = mechanical shaft power of gas turbine (kW)
 P_f = power produced by fuel in SOFC (kW)
 P_{air} = power produced by air in SOFC (kW)
 P_{exh} = power produced by exhaust of SOFC (kW)
 P_{SOFC} = electrical power produced by SOFC (kW)
 \dot{m}_{air} = air mass flow rate of gas turbine (kg/s)
TIT = turbine inlet temperature of gas turbine (K)
 r_{air} = fraction of \dot{m}_{air} going to SOFC
 η_c = compressor efficiency of gas turbine
 η_t = turbine efficiency of gas turbine
 η_{SOFC} = SOFC efficiency
 W_c = compressor work (kJ/kg)
 W_t = turbine work (kJ/kg)

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