Modeling and Analysis of a Hybrid Solid Oxide Fuel Cell – Gas Turbine (SOFC-GT) Combustor System

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Abstract:

This paper presents the steady state modeling and analysis of a Solid Oxide Fuel Cell – Gas Turbine (SOFC-GT) hybrid combustor system. Rising fossil fuel cost and greenhouse gas emissions have renewed interest in high efficiency, low emission power generation, among which fuel cell-gas turbine hybrid cycles are attractive because the high temperature exhaust of the fuel cell can be used directly to drive the turbine. Following a review of the principal fuel cell types and SOFC-GT modeling literature, the Solid Oxide Fuel Cell was selected on account of its solid electrolyte, fuel flexibility and tolerance to impurities. A lumped-parameter, zero-dimensional, steady state model of the hybrid system was developed, comprising an electrochemical model of the SOFC stack incorporating activation, ohmic and concentration losses, together with mass and energy balance models of the combustor, heat exchanger and gas turbine. A representative case study using parameters typical of an anode-supported SOFC operating on internally reformed natural gas predicts a maximum power density of 0.449 W/cm² and a cell electrical efficiency of 51.6% (LHV basis), while the gas turbine sub-model achieves a simple-cycle thermal efficiency of about 19%. Comparison with published hybrid systems indicates that a fully integrated SOFC-GT plant based on this model would achieve an overall electrical efficiency in the region of 55-65%, consistent with previously reported hybrid systems.

Keywords—Solid Oxide Fuel Cell; Gas Turbine; Hybrid System; Combustor; Electrochemical Modeling; Power Generation.

I. INTRODUCTION

World primary energy consumption has increased steadily since the industrial revolution. Fossil-based energy supply, being finite and costly, along with the greenhouse effect linked to anthropogenic emissions, has motivated the search for cleaner and more efficient power generation technologies. Power generation derived from a high-temperature Fuel Cell/Gas Turbine hybrid cycle has attracted considerable attention because such systems are well suited for direct thermal coupling, as the fuel cell and the gas turbine operate with the same working fluid over an overlapping temperature and pressure range.

A fuel cell is an electrochemical conversion device that converts the chemical energy of a fuel directly into electricity through a reaction with oxygen, without an intermediate combustion step, and therefore attains a higher conversion efficiency than conventional heat engines. Fuel cells are classified by the electrolyte material into five principal types: Phosphoric Acid Fuel Cells (PAFC), Polymer Electrolyte Membrane Fuel Cells (PEMFC), Alkaline Fuel Cells (AFC), Molten Carbonate Fuel Cells (MCFC), and Solid Oxide Fuel Cells (SOFC). Table I summarises the conducting ion, electrolyte operating temperature range and principal application of each type.

TABLE I. FUEL CELL CHARACTERISTICS

Fuel Cell	Conducting Ion	Operating Temp.	Application
PAFC	H+	150-200 °C	Distributed power
PEMFC	H+	50-100 °C	Distributed / portable / transport
AFC	OH-	25-250 °C	Portable / backup power
MCFC	$CO3^{2-}$	600-1000 °C	Distributed / electric utility
SOFC	O^{2-}	600-1000 °C	Electric utility / distributed / APU

Among these, the Solid Oxide Fuel Cell (SOFC) is of particular interest for hybridisation with a gas turbine because it operates at 600-1000°C, is fully solid-state (avoiding electrolyte loss, leakage or creep), tolerates fuel impurities such as sulphur and carbon monoxide, and offers fuel flexibility - it can operate on natural gas, reformed hydrocarbons, or hydrogen. Integrated SOFC-GT cycles using natural gas have been reported to reach overall efficiencies of 50-60%, nearly four times the efficiency improvement of the original simple-cycle plant, since the high-temperature SOFC exhaust preheats the fuel and drives the turbine, while the fuel flexibility of the SOFC and reduced NOx formation make the hybrid attractive for both stationary power and transportation auxiliary power units (APUs).

The impact of fuel cells differs across the portable, mobile (transportation) and stationary power sectors. In portable applications, fuel cells compete with batteries, offering quicker refuelling and higher achievable energy density. In mobile applications they compete with internal combustion engines, offering higher part-load efficiency, lower emissions and quieter operation. In stationary power generation, fuel cells are attractive because they are scalable and achieve high efficiency and low emissions even at small scale; when a high-temperature fuel cell such as the SOFC is used, carbon-containing fuel can be utilised directly or with reforming. An SOFC-GT hybrid combines the fuel cell and gas turbine, often with a recuperator to recover waste heat from the turbine exhaust and preheat the compressor discharge air, so that the SOFC exhaust supplies the heat needed to drive the turbine while the fuel is preheated before entering the SOFC, improving overall combustion efficiency. Because the SOFC can generate power comparable to or greater than the turbine alone, and hybrid systems show lower power-degradation at high altitude than conventional heat-based systems, the SOFC-GT configuration is attractive for both distributed stationary power and transportation auxiliary power units.

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II. METHODOLOGY

Based on a review of the available fuel cell types, the SOFC was selected over the Molten Carbonate Fuel Cell for coupling with the gas turbine cycle, primarily because the MCFC suffers from electrolyte evaporation, creep and stack corrosion at high temperature and requires a continuous CO_2 supply at the cathode, whereas the all-solid SOFC construction avoids these problems. The problem addressed in this work may therefore be stated as: to develop a steady state thermodynamic and electrochemical model of an SOFC integrated with a gas turbine, in which the high-temperature exhaust of the fuel cell drives the turbine section, and to analyse the effect of key operating parameters - cell temperature and pressure, fuel and oxidant utilisation, and current density - on the voltage, power output and efficiency of the hybrid system.

A. Modeling Approach

A lumped-parameter, zero-dimensional, steady state approach is adopted. Each component of the hybrid system - the SOFC stack, combustor, heat exchanger (recuperator) and gas turbine - is treated as a separate control volume with defined inlet and outlet states, linked through mass and energy conservation. The SOFC itself is solved using electrochemical relations together with the activation, ohmic and concentration loss mechanisms. This modular structure allows each sub-model to be verified independently before the complete hybrid cycle is assembled.

B. Model Input Parameters and Computational Procedure

The input parameters fall into four groups: operating conditions (cell temperature and pressure, ambient conditions); fuel cell parameters (fuel composition, fuel and air utilisation, exchange current density, area specific resistance, limiting current density, active area, number of cells); combustor/heat-exchanger parameters (combustion efficiency, heat loss fraction, effectiveness); and gas turbine parameters (pressure ratio, isentropic efficiencies, mechanical/generator efficiency, air mass flow rate). The computational procedure consists of specifying the operating conditions, solving the SOFC electrochemical model for the cell voltage at a chosen current density, scaling to stack voltage/current/power using the number of cells, computing the anode and cathode off-gas composition as input to the combustor, solving the combustor energy balance for the adiabatic exit temperature, solving the compressor and turbine isentropic relations, solving the recuperator effectiveness-NTU balance, and iterating (Newton-Raphson) until the mass and energy balances converge, after which the overall first-law and second-law efficiencies are evaluated.

III. MODELING AND ANALYSIS

The SOFC electrochemical reaction proceeds at the three-phase-boundary (TPB): at the cathode, $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$; at the anode, $H_2 + O^{2-} \rightarrow H_2O + 2e^-$ (and $CO + O^{2-} \rightarrow CO_2 + 2e^-$). The electrolyte conducts oxygen ions while electrons flow through the external circuit, giving the overall reaction $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$. Fig. 1 illustrates the electrochemistry of the SOFC.

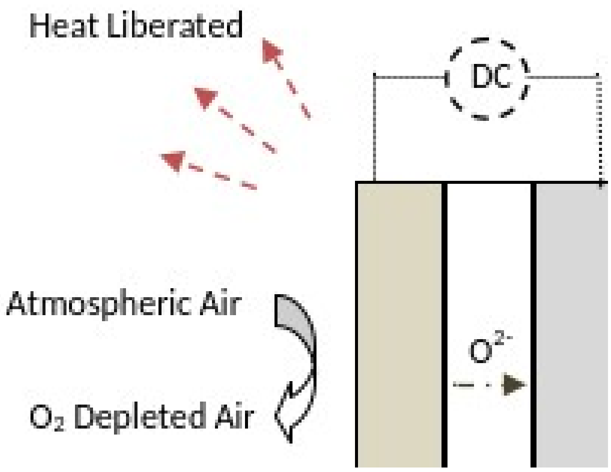

Fig. 1. Electrochemistry of a Solid Oxide Fuel Cell

The reversible (Nernst) cell voltage is given by:

$$E_{rev} = E^\circ + (RT / 2F) \ln [P_{H2} \cdot P_{O2}^{0.5} / P_{H2O}] \quad (1)$$

where E° is the standard reversible potential obtained from the Gibbs free energy change of formation of water at the operating temperature, R the universal gas constant, T the cell temperature, F Faraday's constant and P the species partial pressures. The actual operating (terminal) voltage is lower than E_{rev} due to three voltage-loss mechanisms:

$$V_{cell} = E_{rev} - V_{act} - V_{ohm} - V_{conc} \quad (2)$$

Activation (polarisation) losses arise from the extra potential required to drive the electrode reaction at a finite rate above the exchange current density, and are dominant at low current densities; they are modelled using the Butler-Volmer relation. Ohmic losses arise from the resistance to ionic and electronic current flow and are proportional to current density through the area specific resistance (ASR); $V_{ohm} = i \times ASR$. Concentration (diffusion) losses arise because reactant transport through the porous electrode to the TPB is diffusion-limited, causing the voltage to fall steeply as the current density approaches the limiting current density i_L. The cell electrical efficiency (LHV basis) is:

$$\eta_{ele} = V_{cell} \times 2F / |\Delta \bar{h}_f| \quad (3)$$

The stack voltage, current and power follow from the number of cells (N_{cell}) connected in series and the active area (A): $V_{stack} = N_{cell} \times V_{cell}$, $I_{stack} = i \times A$, and $W_{stack} = V_{stack} \times I_{stack}$. A seven-species reaction vector (CO, CO_2, H_2, H_2O, N_2, O_2) related to current density through Faraday's law is used to track anode and cathode gas composition, allowing internal reforming of natural gas (via the steam-reforming and water-gas-shift reactions) to be represented.

The unspent anode off-gas and cathode exhaust are combusted in an adiabatic combustor, modelled by a species and energy balance in which the enthalpy of the reactants equals the enthalpy of the products; the combustor exit temperature is obtained iteratively (Newton-Raphson). The high-temperature combustor exhaust then drives the gas turbine, whose compressor and turbine outlet states are obtained from the isentropic relations:

$$T_{2s} = T_1[1+(1/\eta_c)(Pr^{((k-1)/k)} - 1)];\ T_{4s} = T_3[1 - \eta_t(1 - Pr^{(-(k-1)/k)})] \quad (4)$$

where η_c and η_t are the compressor and turbine isentropic efficiencies, Pr the pressure ratio and k the specific heat ratio. Compressor and turbine work are obtained from the enthalpy differential between inlet and outlet states, $W_c = \dot{m}(H_{in} - H_{out})$ and $W_t = \dot{m}(H_{in} - H_{out})$. Fig. 2 shows the schematic layout of the integrated SOFC-GT hybrid system used in the present model, in which the recuperator preheats the compressor discharge air using the turbine exhaust before it enters the SOFC cathode.

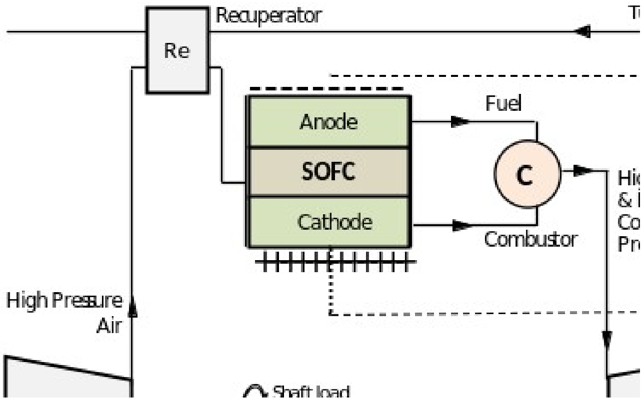

Fig. 2. Schematic Diagram of the SOFC-GT Hybrid System

The general modeling assumptions adopted are: steady-state operation; complete combustion of fuel in the SOFC and combustor; direct fuel supply to the cell; adiabatic (insulated) components; uniform temperature, composition and pressure within each component; chemical equilibrium of reactions; anode, cathode and reformer outlet temperatures equal to the cell temperature; and complete combustion of the residual anode species and injected fuel in the combustor.

IV. RESULTS AND DISCUSSION

A representative case study was computed using parameters typical of an anode-supported, intermediate-to-high-temperature SOFC operating on internally reformed natural gas, coupled to a small single-shaft gas turbine, following the computational procedure of Section II. Table II lists the SOFC operating parameters used.

TABLE II. SOFC CASE-STUDY OPERATING PARAMETERS

Parameter	Value
Cell operating temperature, T	1073 K (800°C)
Cell operating pressure, P	3 atm
Anode inlet composition	H_2 = 70%, H_2O = 30%
Cathode inlet composition (air)	O_2 = 21%, N_2 = 79%
Exchange current density, i_0	0.10 A/cm²
Area specific resistance, ASR	0.30 Ω·cm²
Limiting current density, i_L	1.40 A/cm²
Charge transfer coefficient, α	0.5

Using Eq. (1) the standard reversible potential at 800°C is E° = 0.990 V, and applying the Nernst relation with the compositions of Table II gives an open-circuit voltage of E_{rev} = 1.018 V. The activation, ohmic and concentration voltage losses were evaluated as functions of current density, and the resulting cell voltage and power density curves are plotted in Fig. 3.

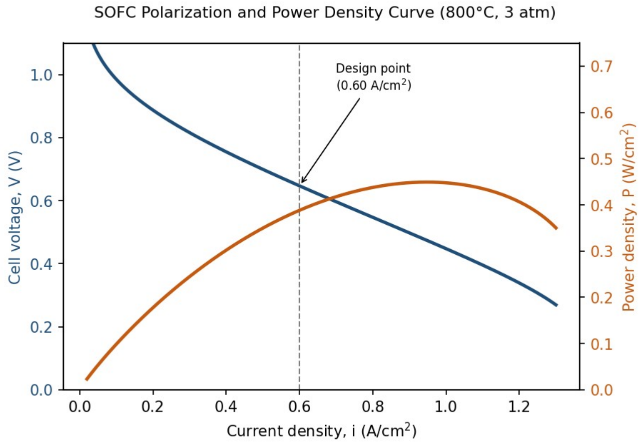

Fig. 3. SOFC Polarization and Power Density Curve for the Case Study

As Fig. 3 shows, the cell voltage falls steadily with increasing current density due to the activation, ohmic and concentration losses, while the power density rises to a maximum of 0.449 W/cm² near 0.95 A/cm², beyond which the rapidly increasing concentration loss causes it to fall. A design operating point of 0.60 A/cm² was selected, away from the limiting-current knee; the corresponding performance for a 100-cell stack (100 cm² active area per cell) is summarised in Table III.

TABLE III. SOFC PERFORMANCE AT THE DESIGN POINT (I = 0.60 A/CM²)

Quantity	Value
Reversible (Nernst) voltage, E_{rev}	1.018 V
Activation loss, V_{act}	0.166 V
Ohmic loss, V_{ohm}	0.180 V
Concentration loss, V_{conc}	0.026 V
Cell operating voltage, V_{cell}	0.647 V
Power density	0.388 W/cm²
Stack voltage / current	64.7 V / 60 A
Stack power output	≈ 3.9 kW
Cell electrical efficiency (LHV)	51.6%

The theoretical maximum electrical efficiency at open circuit is 81.3%; the gap between this value and the 51.6% design-point efficiency reflects the voltage losses incurred in delivering useful current. The gas turbine sub-model, solved independently using Eq. (4) for a compressor pressure ratio of 3.5, turbine inlet temperature of 1123 K, and an air flow rate of 0.45 kg/s, yields a compressor work of 72.9 kW, a turbine work of 129.8 kW, a net shaft output of about 56.9 kW, and a simple-cycle thermal efficiency of only about 19.0% - typical of a small, unrecuperated turbine, and considerably lower than the SOFC stand-alone efficiency. This shortfall is precisely what the hybrid arrangement is intended to address, by using the fuel cell as a high-temperature topping cycle ahead of the turbine.

Table IV compares the sub-system results obtained here with overall efficiencies reported for SOFC-GT hybrid systems in the literature.

TABLE IV. COMPARISON OF REPORTED OVERALL EFFICIENCIES FOR SOFC-GT HYBRID SYSTEMS

Study	Configuration	Reported Overall Efficiency
Cheddie	SOFC into 10 MW GT plant	30.0% → 66.2% (optimised)
Ali, O. et al.	Biomass-fed SOFC/GT, 4-stage	74.4%
Chinda, P. et al.	SOFC/GT aircraft APU	45.1% (vs 42.0% baseline)
Milliner, J. et al.	Pressurised SOFC/GT aircraft	Combined power ≈ 2× SOFC alone
Present case study	SOFC stack + simple-cycle GT	51.6% / 19.0% individually; 55-65% expected integrated

The stand-alone cell-level efficiency of 51.6% already falls within the range reported for SOFC stacks in the literature. The consistent trend reported by Milliner et al., Cheddie, and Ozgoli et al. is that combining the fuel cell with a turbine topping/bottoming arrangement raises overall plant efficiency substantially above either sub-system alone - from 30.0% to 66.2% in Cheddie's case, and to almost twice the SOFC-alone power output in Milliner et al.'s case. On this basis, a fully integrated SOFC-GT plant built around the present sub-models would be expected to achieve an overall first-law electrical efficiency in the region of 55-65%, consistent with the 50-66% range reported in the literature, with the exact value depending on the degree of heat recuperation and the split of power between the fuel cell and the turbine.

V. CONCLUSION

A steady state electrochemical and thermodynamic model of a Solid Oxide Fuel Cell integrated with a gas turbine was developed and exercised through a representative case study. The Solid Oxide Fuel Cell was found to be better suited than the Molten Carbonate Fuel Cell for this application, primarily on account of its solid electrolyte and consequent freedom from electrolyte leakage and creep. The SOFC electrochemical model, incorporating activation, ohmic and concentration losses, predicts a polarisation behaviour and a maximum power density of 0.449 W/cm² consistent with trends reported for anode-supported SOFCs in the literature. The gas turbine sub-model confirms that a simple, unrecuperated turbine cycle alone achieves only a modest thermal efficiency of about 19%, reinforcing the case for hybridisation with the fuel cell. Comparison with the literature indicates that an integrated SOFC-GT hybrid plant based on the present model would be expected to achieve an overall electrical efficiency in the region of 55-65%, roughly one and a half to two times that of either sub-system operating in isolation. The modular, component-wise structure of the model allows it to be extended in a straightforward manner to alternative fuels, stack sizes and turbine configurations - directions that include dynamic/transient modeling, experimental validation, degradation modeling, advanced load-sharing control strategies, thermo-economic optimisation, alternative fuels and carbon capture, and higher-fidelity multi-dimensional cell modeling, each of which would further improve the fidelity and practical applicability of the present steady state model.

FUTURE SCOPE

While the present work establishes a steady state model of the SOFC-GT hybrid combustor system, several extensions would improve both its fidelity and its usefulness for practical system design. Extending the model to a dynamic, time-dependent formulation would allow start-up, shut-down and load-following behaviour to be studied, which is important for transport and part-load stationary applications. Validating the model against measured data from a laboratory-scale SOFC stack, and if possible a small hybrid test rig, would allow the assumed loss coefficients (ASR, exchange current density, limiting current density) to be tuned to a specific cell design. Long-term degradation effects such as nickel sintering at the anode, chromium poisoning of the cathode, and interconnect creep, which govern stack life, could be incorporated as a further sub-model. Development of a control strategy that keeps the fuel cell at a near-constant load while the turbine follows the transient demand is a natural extension, as is combining the present thermodynamic model with capital and operating cost functions to identify the thermo-economically optimum operating point and stack size. The fuel flexibility of the SOFC could be explored further by extending the model to biogas, ammonia and hydrogen-natural gas blends and by examining oxy-anode combustion for CO2 capture. Finally, the zero-dimensional, lumped-parameter approach could be replaced by a one-dimensional or CFD-based model to capture spatial variations in temperature, current density and species concentration across the cell, and the present case-study scale could be extended to specific target applications such as a stationary distributed-power plant or an aircraft auxiliary power unit, each of which places different demands on stack size, weight and transient response.

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