STEADY STATE MATHEMATICAL MODELING OF SOLID OXIDE FUEL CELL FOR HYBRID SYSTEM OF FUEL CELL AND GAS TURBINE (FC-GT)

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ABSTRACT

Looking for alternatives to the source of energy that would be enhanced with respect to environment regards the pollution free surrounding leads to the fuel cell system.

The fuel cell categorized as Solid Oxide Fuel Cell has very high operating temperature (ranges from 650-1050℃) and with positive features, like utilization of exhaust gas, high energy conversion efficiency and fuel flexibility can be utilized and applied to integrate with the traditional power generating technologies, and thus were sometime called an upcoming contrivance of hybrid technology.

Over to gas turbine the fuel cell provide integrated hybrid system of Solid Oxide Fuel Cell and Gas turbine as SOFC-GT hybrid system. Here, a steady state modeling is done for this hybrid system based on the empirical formula and as possible consideration of component of the system, for evaluating a mathematical model for the same.

Keywords: Fuel cell, Fuel Flexibility, Hybrid, Mathematical Model, Solid Oxide Fuel Cell.

1. INTRODUCTION

The assimilation of Fuel Cell into the Gas turbine is of greater interest in last few decades as the world air emission regulations is being austere to research for green clean technology in power generation. Gas turbine supposed to have wide range of application from spacecraft, airplanes to turbo road cars, and other auxiliary power units. The internal combustion engine complicated to get environmentally optimized without compromising the fuel efficiency.

The feature of the fuel cell named Solid Oxide Fuel Cell best suited for hybrid systems on amalgamation with conventional turbine power plants offering high cycle efficiencies as they work on high operating temperature nearly about 650– 1050 C.

A SOFC can be of Tubular or planer geometry, i.e. simplest geometry. Fig. 1 shows stack geometry of SOFC, (a) Tubular and (b) Planer.

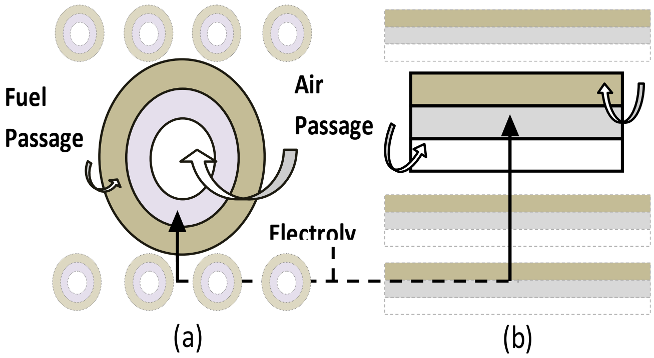

Fig. 1 geometry of Solid Oxide Fuel Cell

Fuel flexibility enables natural gas, carbon monoxide, methanol, ethanol and hydrocarbon compound as well as hydrogen to use as a fuel in SOFC.

Like a typical fuel cell Solid Oxide fuel cells converts a fuel's chemical energy into electricity, SOFCs are expected to be around 50–60% efficient at thermal efficiency, with other benefits as light weight and low volume, rapid startup and peak load management for battery SOFC hybrid systems, direct conversion of fuel to electricity, not restricted to pure hydrogen or particular specified fuel, tolerant of impurities and poisons (as compared to proton-exchange-membrane, PEM fuel cells) the electrolyte used are the hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O_2) as electrolyte.

Gas turbine works on Brayton cycle with its main elements as compressor, combustor and the gas turbine. The compressor is to constrict the intake air to provide necessary pressure, combustor use the upcoming pressurized air from the compressor to burn it at constant pressure and thus to exhaust to the turbine for expansion and finally extract power for compressor and generator.
Other element like heat exchanger, pre-heater or they also can be place in between cycle for better performance efficiency.

The integration of SOFC to the gas turbine can be direct or indirect. Direct integration means to replace combustion chamber with heat exchanger where the air from compressor is heated by exhaust of SOFC.

Via mathematically model of hybrid of this fuel cell and a gas turbine power system a simulation can be performed for the integrated power generation system under steady state

2. MODELING APPROACH

The present analysis is intended to evaluate overall performance of a GT-SOFC hybrid system. A thermodynamic cycle analysis of a recuperative gas turbine coupled with an equilibrium calculation of a SOFC is established to predict design-point and part-load performance. We consider mass and energy balance equations for energy conversion processes in all components. Temperatures, pressures along with the compositions of a working gas at the inlet/outlet of each module are also concerned. Compo net models are independent of their specific factors, i.e., structures of a compressor and turbine, cell geometry, a stack configuration and a type of a reformer. Theoretical expressions are introduced into the cycle analysis to indicate general characteristics of components. Empirical relationships are considered and applied.

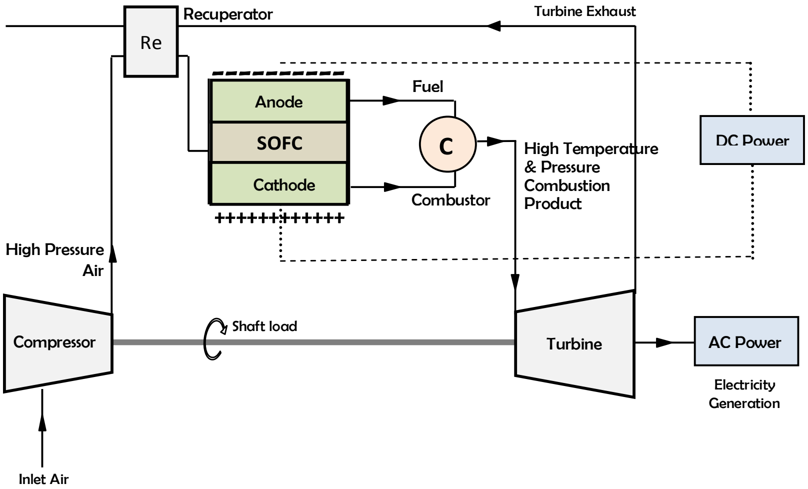

Fig. 2 schematic diagram of SOFC-GT hybrid system

3. MODELING ASSUMPTIONS

Depending upon the application like aerospace, power plant and vehicles the assumption varies, thus the general assumption taken are:

1. Steady-state operation
2. Full combustion of fuel in combustion chamber as well SOFC
3. Direct fuel supply to the fuel cell.
4. All components are insulated, i.e. no loss
5. Uniform distribution temperature, gas composition and pressure in every component.
6. Equilibrium states chemical reactions
7. the temperatures at the outlets of anode, cathode, and reformer are equal to the cell temperature
8. In the combustor, the residual species from the anode and the injected fuel burnt completely.

4. SOLID OXIDE FUEL CELL MODELING

SOFC model considers the open circuit voltage activation losses, Ohmic losses, and concentration (diffusion) losses. Model use the Butler-Volmer rate equation for activation losses, a bulk diffusion and Knudsen diffusion theory for concentration losses, and Ohm’s law for Ohmic losses in the electrolyte. The output voltage correlation is the output voltage verses current density behavior in terms of voltage losses.

$$V_{out} = V_{oc} - V_{act} + V_{ohm} + V_{conc} \tag{1}$$

Now, the number of cell requirement for stack can be evaluated by considering the Voltage desired and the voltage of single cell as

$$N_{cell} = \frac{V_{tot}}{V_{cell}} \tag{2}$$

The space requirement will be given by the area of each cell (A, cm^{-2}) within the stack can be calculated using the single cell current density (I_{cell} , A.cm^{-2}) and the stack current

$$A = \left(\frac{W_{max}}{V_{tot}}\right) \Big/ I_{cell} \tag{3}$$

Nernst voltage

The energy is generated in fuel cell through the electrochemically oxidation reaction occurs in it between the hydrogen and carbon oxide so as to give

$$H_2 + {}^1\!/_2\, O_2 \rightarrow H_2O \tag{4}$$

$$CO + {}^1\!/_2\, O_2 \rightarrow CO_2 \tag{5}$$

Now as the reaction proceed to equilibrium state, using change in Gibbs energy, ΔG_{H2} before and after the reaction of hydrogen, thus Nernst voltage is given by

$$V_{H2} = \frac{1}{2F}\Delta G_{H2} - \frac{RT}{2F} + In\left(\frac{P_{an}\, H_2O}{P_{an}\, H_2\sqrt{P_{Ca.}O_2}}\right) \tag{6}$$

By the use of equilibrium constant mole fraction the EQ can be re-write as,

$$V_{H2} = \frac{RT}{2F}\left\{\text{In}\, K_{H2} - \text{In}\left(\frac{x_{an}\, H_2O}{x_{an}\, H_2}\right) + \frac{1}{2}\,\text{In}(x_{ca}\, O_2\, P_{ca})\right\} \tag{7}$$

Currently, there are uncertainty and arguments whether electro- chemical oxidation of carbon oxide proceed in the SOFC. However, in the current study, for carbon oxide is electrochemically oxidized in the anode

$$V_{CO} = \frac{RT}{2F}\left\{\text{In}\, K_{CO} - \text{In}\left(\frac{x_{an}\, CO_2}{x_{an}\, CO}\right) + \frac{1}{2}\,\text{In}(x_{ca}\, O_2\, P_{ca})\right\} \tag{8}$$

Utilization factor of the fuel and oxygen are defined as ,

$$U_{H2} = n_{H2,\text{consumed}}/n_{H2,supplied} \tag{9}$$
$$U_{O2} = n_{O2,\text{consumed}}/n_{O2,supplied} \tag{10}$$

The generated current is directly obtained from the amount of the reaction species. The power output of the SOFC, is calculated from the net voltage and current.

$$H_{out} = [H_{in} + (-\Delta H_{cell})] - W'_{SOFC} \tag{11}$$

And the overall system efficiency

$$\eta_{sys} = \frac{W_{gt} + W_{SOFC}}{(m_{gt} + m_{SOFC})\Delta H_{fuel}} \tag{12}$$

5. RESULT & DISSCUSSION

The modeling of Solid Oxide Fuel Cell is done with consideration of almost all factor losses like activation losses, Ohmic losses, and concentration (diffusion) losses. And the equation for power output and the system efficiency is mathematically developed.

Still modeling for fuel reformer and other component like compressor, recuperator, and combustor of hybrid system is to be carried out.

This is supposed have huge area of modeling and other consideration with need of some practical assumptions

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