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Use of zero-dimensional modelling to predict performance and assess feasibility of solid oxide fuel cell-gas turbine hybrid system

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Abstract.
This study looks at a steady state and a dynamic model of a solid oxide fuel cell-gas turbine (SOFC-GT) system. The steady state model is used to perform a sensitivity analysis of the system's electrical efficiency to design parameters at design point, while the dynamic model is used to predict key performance indicators across the operating range of the system. Electrical efficiency at the design point was found to be most sensitive to gas turbine pressure ratio and SOFC temperature. Power output was increased from the baseline to peak on the dynamic model and peak electrical efficiency was found to be 0.61 at 58% load.

Keywords. SOFC, Gas Turbine, Hybrid System, Zero-dimensional Model.

1. Introduction

Solid oxide fuel cells (SOFC) are solid-state electrochemical devices that convert chemical energy of fuel into electrical energy with more than 65% efficiency at temperatures higher than 650□C [1]. However, they have poor response to transient load demands under dynamic operating conditions, which make them unsuitable for aircraft and automotive applications. One solution to this is hybridising with a Brayton cycle gas turbine generator to form a system, as shown in Figure 1, that combines the high efficiency of the SOFC and dynamic performance of the gas turbine [2]. Previous research has found that the best operating strategy for such a system is having the SOFC operating at steady state and providing the baseline power with the gas turbine covering load increments above that baseline.

The purpose of this study was to develop numerical models of SOFC-GT systems that can be used in the early stages of product development. Therefore, zero-dimensional models were created due to their low computational cost, which is important for performing feasibility studies, sizing, and systems engineering. Two models were developed and applied on this study namely:
1) Steady-state model: Algebraic equations governing the components are modelled in their time-independent form. This model was used to simulate the system at various values of design parameters – gas turbine pressure ratio, SOFC temperature, and pre-heater effectiveness – with no variation in input and output conditions. The results of these simulations were analysed for correlation of those design parameters with electrical efficiency of the system.
2) Dynamic model: Components are modelled using first order differential equations that govern the phenomena occurring in them to simulate time-dependent behaviour. A SOFC-GT system model was built and simulations were run from baseline to peak power by changing the shaft speed and fuel flowrate being fed to the system.

The purpose of these steady state and dynamic simulations was to find the correlation of electrical efficiency with design parameters and operating conditions respectively. This is because efficiency is the most important performance indicator when it comes to power sources for decarbonising transport [2].

2. Simulation Method

For both models, mass and energy conservation equations were applied to model the various components of the system which consists of compressor, turbine, heat exchangers, combustor, and SOFC [3]. Typical values for electrochemical parameters were used for the SOFC models [1] and the following assumptions were made:

- The fuel cell, turbine, compressor, heat exchangers, and burner are considered as individual lumped systems, i.e., each of them is a separate control volume.
- Pressure losses and heat transfer in piping, manifolds and other connecting devices between the sub-systems are negligible.
- Ideal gas behaviour is assumed for fuel and oxidant flow streams.
- Heat losses from the fuel cell stack to the environment is negligible.

A. Steady State Model

100 sets of randomised values of turbine pressure ratio (PR), fuel cell temperature (Tfc), air stream pre-heater effectiveness (HXae), and fuel stream pre-heater effectiveness (HXfe) were generated within their respective practical limits, and inputted to the numerical

model to determine system efficiency (defined as ratio of electrical power output to Lower Heating Value of fuel used) for each parameter set.

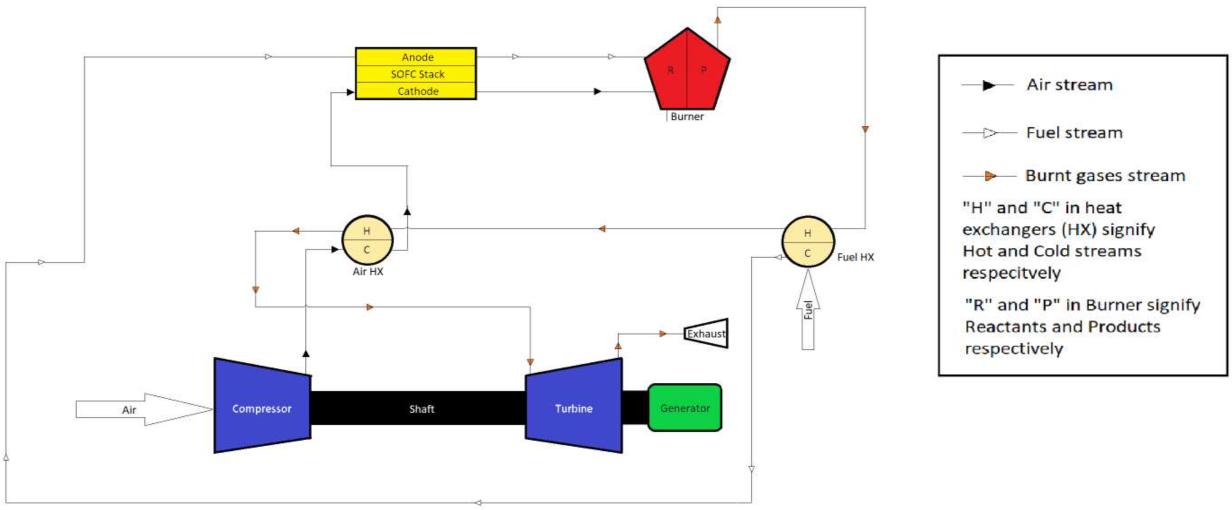

Fig. 1. Schematic of a SOFC-GT system.

B. Dynamic Model

The SOFC power output was maintained at around 65 kW and gas turbine power was increased from 0 kW to 95 kW in steps by increasing the fuel fed to the burner and consequently, shaft speed. Performance maps from literature were used to model the GT compressor and turbine [4].

3. Results and Discussion

Data from the steady state simulations were analysed to determine the correlation of efficiency with the chosen design parameters. Turbine pressure ratio (PR) and fuel cell temperature (Tfc) showed the highest correlation of 0.702 and 0.504 to system efficiency as shown in the tornado plot in Figure 2.

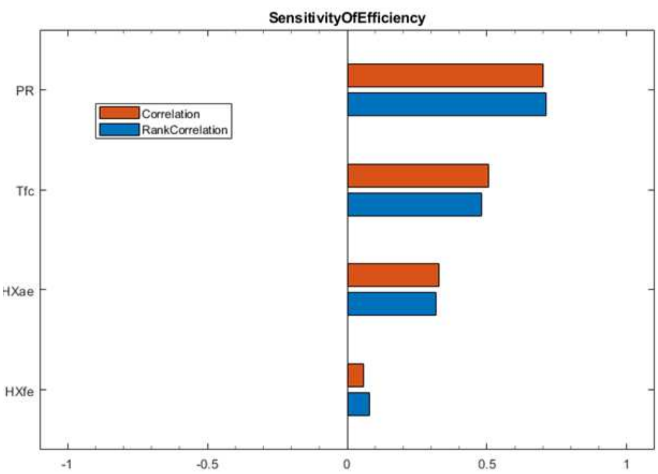

Fig. 2. Tornado plot from sensitivity analysis of steady state simulation results.

Results from the dynamic simulation (Figure 3) show that the system is capable of a peak efficiency of 61% at 95 kW combined power output. When gas turbine shaft speed is increased to increase GT power output, the pressure of the air stream going into the SOFC is increased too. The gradual increase in SOFC power output is caused by this increase in partial pressure of reactants leading to an increase in Nernst voltage. System efficiency also gradually increases up to the peak due to this. However, additional fuel is added to the GT combustor to increase shaft speed past this point and efficiency drops.

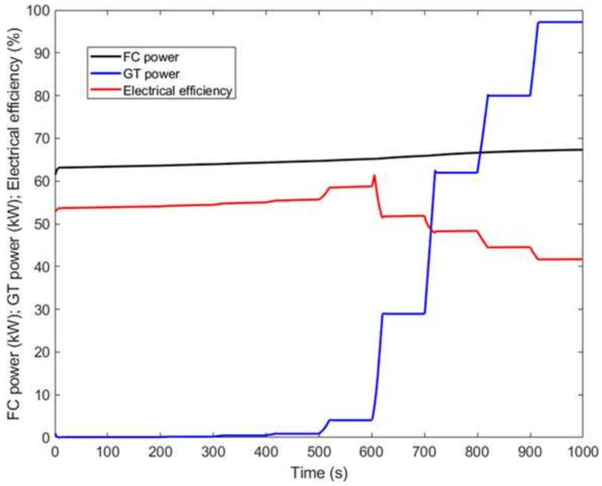

Fig. 3. Dynamic simulation results for SOFC-GT system power outputs and efficiency

4. Conclusion

Numerical models of SOFC-GT systems were developed and tested in steady state and dynamic simulations to identify the correlation of design parameters and operating conditions with electrical efficiency of the system. These models can be used in sizing, feasibility studies, and control design of SOFC-GT system development in the future.

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