Improving Hybrid Efficiency and Flexibility by Integrating Thermal Energy Storage into the Fuel Cell System

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ABSTRACT

This concept directly incorporates thermal energy storage (TES) within a solid oxide fuel cell (SOFC). The SOFC interconnect thickness was employed as a storage medium. By increasing it's thickness the benefits were quantified to demonstrate the potential for improving the flexibility of fuel cell hybrid power systems and increasing the efficiency in standalone fuel cell systems. A significant amount of energy can be recovered without damage to the fuel cell when thermal energy storage was incorporated in the SOFC design. Also, less airflow was required on the cathode for thermal management when the thermal mass of the fuel cell was increased. The ohmic losses were predicted to decrease, thereby leading to higher cell voltage and system efficiency.

Keywords: solid oxide fuel cell, thermal energy storage, fuel cell heat capacity, fuel cell interconnect, fuel cell gas turbine hybrid

1 INTRODUCTION

Operational flexibility is required to the demands of the new paradigm arising from an electric power market comprised of large contributions from intermittent sources while ensuring economic feasibility. A primary objective of advanced power generating systems is to be capable of adjusting to electric load demands. Thermal energy storage (TES) can be added to the system to increase its flexibility. Hybrid systems can couple multiple advanced technologies to achieve this type of system flexibility, while maintaining other critical objectives including high overall efficiencies and outstanding environmental performance. In this way hybrid technologies can reduces dependency on fossil fuels, preserving them for future generations, while taking advantage of their availability and reliability to maintain a clean and robust power grid. Solid oxide fuel cells (SOFC) operate between 600 and 1000 ˚C at high efficiencies, making this an ideal and highly efficient power system with potential to store large quantities of thermal energy. This stored energy can be readily utilized when coupled with gas turbines, another highly efficient and reliable.

It is well known that TES can be used to resolve the problems associated with intermittent power production when it is combined with renewable energy[1–3]. When TES is integrated with systems using gas turbines for combined heat and power (CHP) electricity demand can be matched with power production. There have been a number of variations reported in which fuel cells play a role in load following concepts. As an electrolysis cell the SOFC is operated in reverse to becomes an energy storage device [4, 5]. Another concept is to store energy in the form of hydrogen by integrating the SOFC with metal hydride tanks for [6–8].

The concept developed by National Energy Technology Laboratory (NETL) does not require the costs of separate energy storage devices only alterations to the design and development of a dynamic control strategy. In addition, these design and control changes will promote system stability, making the hybrid more robust and viable. SOFCs have high heat capacities, mainly due to their large mass of interconnect material necessary to extract the electrical current. The interconnect material is typically composed of stainless steel which has a relatively large specific heat compared to the materials of construction for the cathode, anode, and electrolyte. Conventionally, the amount of interconnect material is minimized to reduce costs [9]; however, in this concept it is recognized that there are a number of possible advantages to designing an interconnect material to promote thermal energy storage. In a hybrid configuration SOFCs can be used as TES for active power control to dramatically increase system dynamic flexibility.

2 METHODOLOGY

NETL's concept is to incorporate TES directly into the fuel cell design [10]. This concept was developed using the Hybrid Performance project facility, as shown in

Figure 1 [11]. A one-dimensional (1D) fuel cell model of a planar, co-flow, anode-supported SOFC was used to study the dynamics of thermal energy storage in solid oxide fuel cells. This fuel cell model was previously developed and validated in MATLAB Simulink® [12].

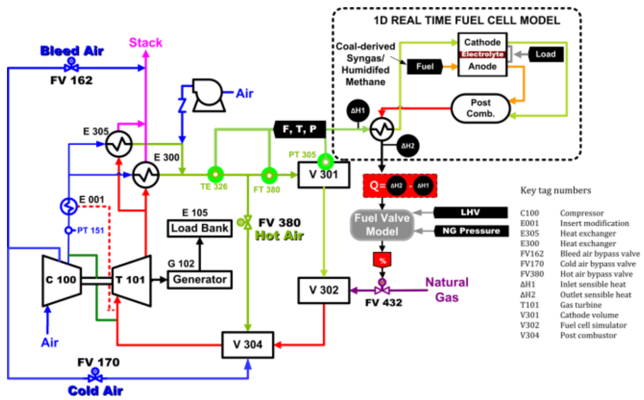

Figure 1. Schematic diagram of Hybrid Performance project at National Energy Technology Laboratory (NETL). The 1-D fuel cell model is shown the dashed-line box

The nature and amount of interconnect material in the SOFC was varied and the effect on the hybrid power system was evaluated. The thickness of the interconnect material was varied over 6 discrete levels in a 500 kW SOFC system using syngas fuel composition (Table 1). The nominal case had a total mass of 3,500 kg with 3,080 kg of stainless steel interconnect for all 2,500 cells (i.e., 88% mass shown in Table 1). The fuel cell was operated at a constant 220 A total current. This resulted in a fuel utilization 67% over the entire stack.

Table 1. SOFC interconnect mass and thermal storage

Interconnect Mass (kg)	Percent Mass of Total SOFC	Heat Capacity (kJ/K)
308	42	1350
1540	79	1917
3080	88	2625
6160	94	4042
15400	97	8292
30800	99	15376

3 RESULTS AND DISCUSSION

The total heat capacity was increased by increasing the mass of the interconnects within the fuel cell. For example, a 500 kW SOFC at the nominal or baseline condition had approximately 2.6 GJ of stored thermal energy. This represents the total amount of thermal energy that is stored within this fuel cell. While thermodynamic laws do not permit all of this heat to be extracted and used, an amazingly large amount of energy was found to be available to the gas turbine in a hybrid configuration within 100 ms [13]. In addition, by modifying the design and materials of construction this amount of energy can be easily doubled, substantially improving the capacity of the SOFC as a dynamic thermal energy storage device. During transient operation, heat could be stored or removed without adversely affecting the temperature gradient within the fuel cell, dramatically increasing system flexibility.

The steady state temperature profile was found to be more uniform across the length of a fuel cell stack with larger interconnect mass (Figure 2). Another benefit of increasing interconnect size is the resulting increase in stack efficiency (Figure 3). The increased cross section area in the interconnects reduces ohmic losses. The more uniform temperature profile reduces activation losses. The uniform temperature profile has the additional advantage of decreasing the cooling airflow requirements. All three of these results lead to increased power system efficiencies.

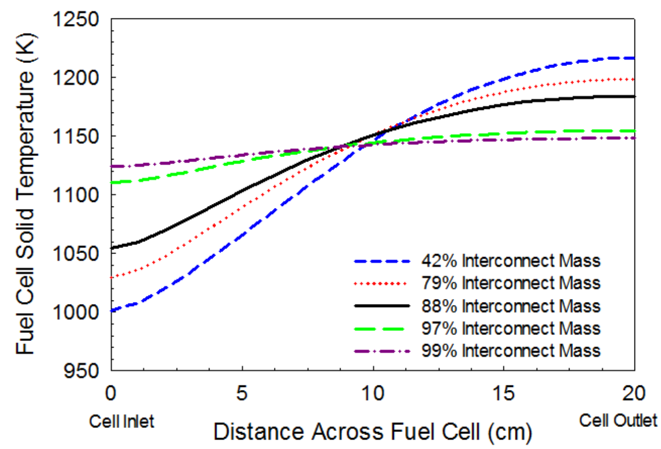

Figure 2. Temperature distribution across the fuel cell for different interconnect mass relative to the nominal condition (88% interconnect mass).

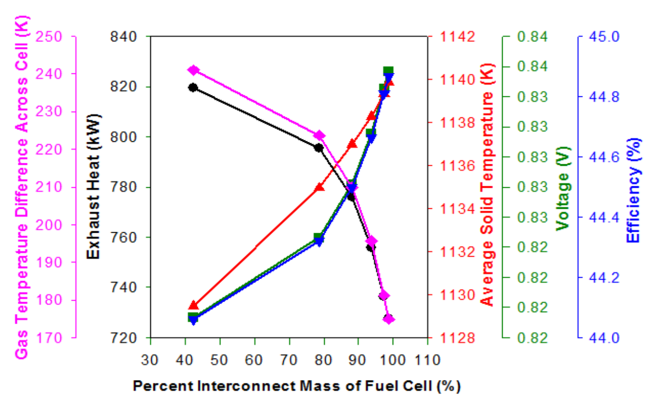

Figure 3. The effect of interconnect mass on the fuel cell performance parameters including gas and solid temperatures, voltage, exhaust heat, and efficiency.

In a hybrid system, flexibility is significantly increased when thermal energy can be extracted and converted to electricity in a recuperated turbine cycle. Thermal energy extracted from the fuel cell in a direct fired hybrid system, as shown in Figure 4, can be converted into electricity using the recuperated gas turbine cycle. In this system, thermal energy can be readily accessed by several means. In Figure 5 the thermal energy was extracted during a hyper test operation by stepping up the cathode airflow rate. This is arguably the most direct manner of extracting the thermal energy stored in the fuel cell. In the Hybrid configuration this increase in the cathode airflow can be achieved by changing one of several bypass valves (FV-162, 170, or 380). The choice of which control valve to use for this dynamic operation will depend upon the operational state of the system and other process constraints.

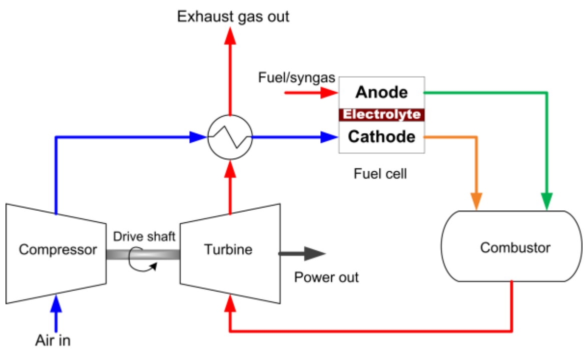

Figure 4. A direct fired hybrid power cycle consisting of a fuel cell topping cycle with a recuperated gas turbine bottoming cycle.

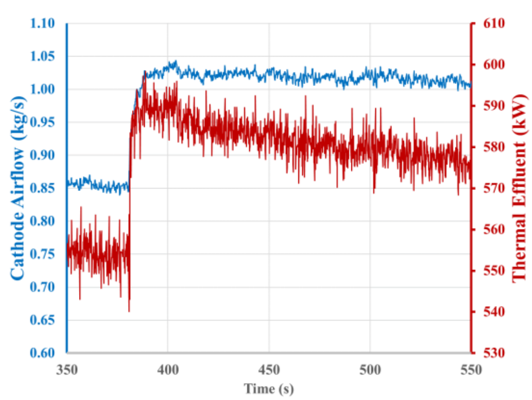

Figure 5. The effect of cathode airflow step change on the thermal effluent from the fuel cell system.

Increasing the airflow by 15%, the turbine output was nearly doubled instanteously. As shown in Figure 5 this cathode airflow change extracted an additional 40 kW of heat from the fuel cell and delivered it within milliseconds to the turbine. That elevated power output was sustained over the next several minutes, albeit with slightly diminishing returns over time.

The temperature gradient along the cells in a fuel cell stack were reduced dramatically with increased interconnect mass (Figure 6). Increasing the interconnect mass by a factor of 10 resulted in a 6-fold drop in the peak temperature gradient. This peak occurred in the initial 25% of the fuel cell stack for the syngas fuel tested. Decreasing the interconnect material by 10, on the other hand, moved the peak temperature gradient towards the center of the stack while exacerbating the temperature gradient. In the minimal interconnect case the peak temperature gradient was nearly 50% higher than the nominal case. Increasing the interconnect size and cross sectional area increased the overall thermal conductivity and reduced the temperature gradient along the cell. This makes the cell more tolerant to changes in the cathode cooling airflow, which in turn, can be used for recovery of stored thermal energy in the fuel cell. Thus, increasing the mass, or heat capacity, of the fuel cell interconnects can reduce the temperature gradients across the fuel cell and make it more robust so that control schemes can be developed to achieve the desiarable load following characteristics.

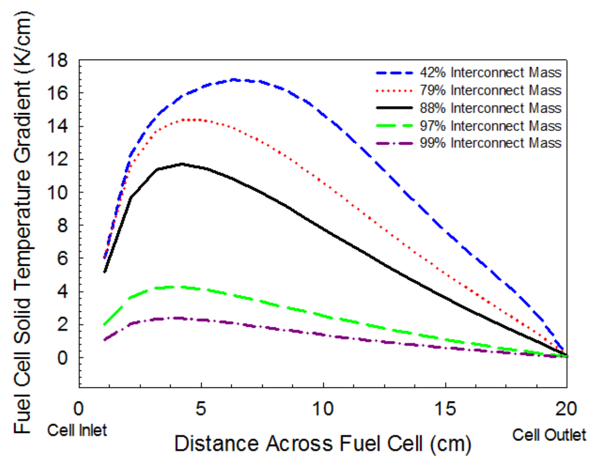

Figure 6. Solid temperature gradients along the fuel cell stack in a solid oxide fuel cell system for varying interconnect sizes (nominal case 88% interconnect mass).

4 CONCLUSION

Dynamic testing of a more robust fuel cell concept was conducted using the Hybrid Performance project facility at NETL. The hyper tests demonstrated the ability to extract large amounts of thermal heat from a fuel cell and increase the electric load within milliseconds. These tests were augmented by steady state model analyses in which the mass of fuel cell interconnect material was varied. From the analysis it was concluded that additional stored heat also improved performance characteristics of the fuel cell itself. The fuel cell became more efficient, lasted longer, and in general, was more robust to dynamic perturbations.

It is apprent that the optimum interconnect mass will depend upon the value assessed to the improved flexibility, life expectancy, and working parameters of the fuel cell relative to its capital cost. Additional work is required to determine how to best include TES in the SOFC to achieve the desired dynamic performance of the system when coupled with a gas turbine.

5 ACKNOWLEDGMENTS

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DISCLAIMER

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