Title

Development of controls for dynamic operation of carbonate fuel cell-gas turbine hybrid systems

Authors

Roberts, Rory A
Brouwer, Jack
Liese, Eric
et al.

Publication Date

2005

Proceedings of GT2005
ASME Turbo Expo 2005: Power for Land, Sea and Air
June 6-9, 2005, Reno-Tahoe, Nevada, USA

GT2005-68774

DEVELOPMENT OF CONTROLS FOR DYNAMIC OPERATION OF CARBONATE FUEL CELL-GAS TURBINE HYBRID SYSTEMS

Rory A. Roberts, Jack Brouwer
National Fuel Cell Research Center
University California, Irvine

Eric Liese, Randall S. Gemmen
National Energy Technology Laboratory
Morgantown, WV

ABSTRACT

Hybrid fuel cell/gas turbine (FC/GT) systems have been shown through experiment and simulation to be highly efficient technologies with low emissions. Maintaining efficient, low emission, and safe operation, whether during disturbances or regular operational transients, is a challenge to both understand and address. Some likely disturbances can arise from changes in ambient temperature, fuel flow variations induced by supply pressure disturbances, fuel composition variability, and power demand fluctuations. To gain insight into the dynamic operation of such cycles and address operating challenges, dynamic modeling tools have been developed at two different laboratories. In this paper these models are used to simulate the dynamic operation of an integrated MCFC/GT hybrid system and to subsequently develop and test control strategies for the hybrid power plant. Two control strategies are developed and tested for their ability to control the system during various perturbations. Predicted fuel cell operating temperature, fuel utilization, fuel cell and GT power, shaft speed, compressor mass flow and temperatures throughout the FC/GT system are presented for the controlled response to a fuel cell voltage increase in order to show the effect of a load decrease.

KEYWORDS: *Molten Carbonate Fuel Cell, Gas Turbine, Hybrid, Controls, Dynamic Simulation*

INTRODUCTION

Hybrid cycles comprised of high temperature fuel cells, such as the molten carbonate fuel cells (MCFC) or solid oxide fuel cells (SOFC), will likely be the preferred method for generating electric power in the future, initially at the small to medium scale (250 kW to 20 MW), and later in large scale central plants (>100 MW). However, hybrid FC/GT systems are in need of significant advancement before they are introduced as commercial products. Some progress is needed to address the specific challenges that are introduced by coupling a fuel cell with a gas turbine given their disparate dynamic response characteristics.

The FC/GT hybrid concept has been around for over 30 years, but the concept has only been demonstrated by two systems in the past five years. Siemens Westinghouse (SW) developed a 220 kW hybrid system using their tubular solid oxide fuel cells and an Ingersol-Rand GT. This system was a direct topping hybrid cycle that placed the SOFC between the compressor and turbine and pressurized the SOFC to above 3 atmospheres. The system proved the hybrid concept by generating electricity at fuel-to-AC electricity efficiencies up to 53% with near zero emissions at 200 kW. This world record efficiency (at such a small power plant size) resulted from the synergy of hybrid FC/GT plant concepts. The hybrid FC/GT concept can improve fuel cell performance while converting some of the fuel cell thermal product into electricity in the GT. This system was tested at the National Fuel Cell Research Center (NFCRC) for approximately 3000 hrs [1].

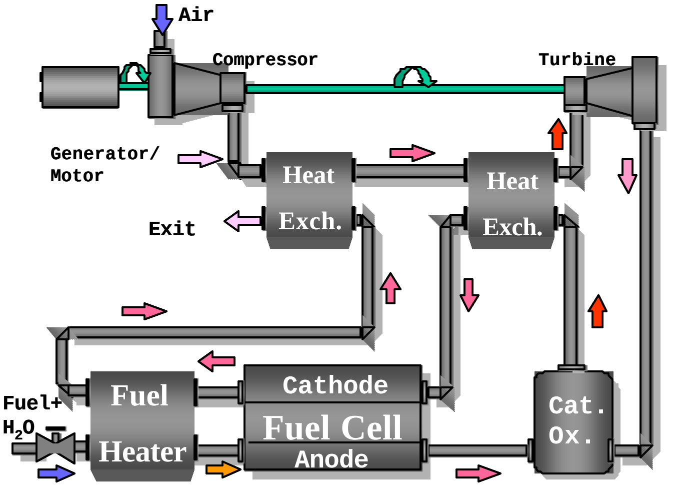

Figure 1. Hybrid indirect internal reforming fuel cell bottoming cycle after FuelCell Energy's DFC/T™ cycle

FuelCell Energy (FCE) developed and tested a second hybrid system. The Direct FuelCell™/Turbine (DFC/T™) system provided 210 kW of AC power in grid-connected mode and achieved a fuel-to-AC electricity efficiency of 51.7% [2]. The system operated for approximately 2900 hrs with the GT running and 6800 hrs of operation with just the molten carbonate fuel cell (MCFC) running. The work presented in this paper is most directly related to the type of cycle demonstrated by FCE. This type of cycle uses heat exchangers to indirectly provide the excess MCFC heat energy to the GT by operating the fuel cell in the exhaust of the GT. The cycle is thus an indirect bottoming hybrid FC/GT cycle based on the internal reforming DFC/T concept as presented in Figure 1.

Both the SW-SOFC system and the FCE DFC/T system proved the concept of integrating a fuel cell and a GT in a synergistic way to produce electrical power at very high efficiencies and with ultra low emissions. These hybrid systems did this at a small scale (around 200kW) of electricity production. The successes of these demonstrations provide hybrid technology a strong argument for claiming future private and government R&D funding. These systems were not optimized with respect to integration, operation, or system component compatibility. Rather, developmental off-the-shelf components were used in order to speed development and reduce cost. The overall objective for each of these projects was to prove the concept while gathering operational data and developing and testing control strategies. FCE developed and refined shutdown and emergency trip control logic and also developed process and control loops for control of the fuel cell cathode temperature while maximizing the turbine inlet temperature (TIT) [2]. The current paper presents dynamic simulation approaches and results that focus on this latter aspect of hybrid FC/GT process control.

Several entities around the world have developed steady state simulation capabilities for FC/GT systems. These include efforts of the Georgia Institute of Technology [3], University of Genova [4-6], NFCRC [7-9] and others. Dynamic FC/GT simulation capabilities are less common, but increasingly being developed as the demand for dynamic understanding and controls development grows. Examples of previous dynamic simulation efforts include the works of University of Genova, National Energy Technology Laboratory (NETL), FCE, and NFCRC [9-16].

The NFCRC and NETL have developed and demonstrated two different dynamic models in previous work [15, 16]. Experimental data are very valuable assets providing insight and verification in each of the model's simulation capabilities. Unfortunately steady state and dynamic experimental data are nearly impossible to obtain or do not exist at all in the public realm for the integrated FC/GT systems that are being studied in this effort. This was especially true when this effort was initiated (well before the two demonstration systems were tested). As a result, NFCRC and NETL developed a strategy for model development, comparison and validation that has proven to be very useful and productive. In these recent efforts, the authors have been comparing different models from each laboratory, which were built in different simulation platforms, but with the same underlying model parameters and assumptions. Comparing results from the models resulted in very useful feedback, discussion, and discovery of model errors and code bugs. In addition, the comparisons resulted in an alternative means of validating and testing the models' performance.

NOMENCLATURE

AC	Alternating current
DFC/T	Direct Fuel Cell/Turbine
FC/GT	Fuel cell/gas turbine hybrid
FCE	FuelCell Energy
FU	Fuel utilization
GT	Gas turbine
MCFC	Molten carbonate fuel cell
MCFC/GT	Molten carbonate fuel cell/gas turbine hybrid
NETL	National Energy Technology Laboratory
NFCRC	National Fuel Cell Research Center
PID	Proportional, integral & differential controller
R&D	Research and development
SOFC	Solid oxide fuel cell
SW	Siemens Westinghouse
SW-SOFC	Siemens Westinghouse solid oxide fuel cell
TIT	Turbine inlet temperature
U	Input to controller
Y	Output of controller

SIMPLE CATALYTIC OXIDIZER CONTROL

In previous reported work Roberts [16], each model (NFCRC and NETL) simulated the same perturbation to determine an open loop response of a MCFC hybrid plant. The cycle investigated is one that offers good system performance in both efficiency and load following capability. Specifically, for this work, both models simulate the system represented in Figure 1 at a scale of 1MW total output (~850kW from the MCFC and ~150kW from the turbine at design point operating conditions). The two simulation results were then compared in order to verify proper physical modeling in each code. A step load decrease on the MCFC was chosen as the perturbation for testing the simulated dynamic response of the system. Results showed that the GT power increased due the surplus of fuel leaving the MCFC and eventually entering the catalytic oxidizer. The increase in catalytic oxidizer temperature caused an increase in the cathode inlet temperature for the uncontrolled system, a condition that could lead to damage in the MCFC.

This previous work also suggested that simple proportional integral differential (PID) controls could be used to maintain desired process temperatures during such load perturbations. The presumption was, for example, that the control would maintain a proper cathode inlet temperature and, as a result, MCFC operating temperature. Two different control strategies were used. The NETL control adjusted fuel flow to maintain constant fuel cell fuel utilization (FU), and adjusted airflow via the turbine speed in order to maintain the set point catalytic oxidizer temperature. This type of control implies that a variable speed turbine is used for the NETL version of the hybrid plant. The NFCRC control adjusted the fuel flow (to the fuel cell) to maintain the set point catalytic oxidizer temperature, and simply let the FU float. The NFCRC case considered the airflow to be fixed through the use of a fixed-speed turbine. Both control strategies were aimed at controlling ultimately the MCFC temperature. The total plant power was not a controlled parameter but will be a necessary step in the future of the control development of the system. For example, when in a load-following commercial application, the load of the GT and the MCFC will need to be coordinated in order to achieve the desired plant power as demanded from “the grid”. In prior work and in this current work, the dynamics and limitations of the system components and actuators are being investigated. The understanding of these dynamics and limitations will be needed in order to effectively develop the control strategy for safe and efficient control of a load following FC/GT system.

Details of the prior model work are found in Roberts [16]. For convenience, the key results from this work are presented again in Figures 2 through 4. The dynamic power responses of the MCFC/GT system of Figure 1 to a step drop in MCFC load demand are presented in Figure 2. The cathode and catalytic oxidizer temperatures are presented in Figure 3. The fuel flow and utilization histories for this same dynamic response to an MCFC load drop are presented in Figure 4. For both control strategies and simulation results (NFCRC and NETL), the catalytic oxidizer temperature was successfully controlled, but the cathode inlet temperature was shown to decrease slightly for both cases. In addition, the results show that controlling fuel utilization may be beneficial for achieving good system efficiency.

PRESENT APPROACH

From the results of the previous work, it can be seen that the cathode inlet temperature is slightly decreasing. Since the NFCRC control scheme did not reduce the flow through the cathode, there was some concern with this original control scheme that there would be over-cooling in the fuel cell. Therefore, this work will build on the previous work in the following ways.

Both models now simulate a GT with a variable speed capability used to control process temperatures. Such capability allows the compressor load to decrease as overall plant load is decreased, which will result in higher plant efficiency. Further, at this time it is proposed that the fuel cell should maintain a fixed FU under variable load, which is beneficial for achieving high efficiency within the fuel cell as load decreases.

The development of such a control strategy for hybrid fuel cell operation is valuable since simple cycle fuel cell systems (without GT) also benefit from such capability. That is, the control system for the fuel cell could be the same for a hybrid as for a simple cycle fuel cell, which provides consistent fuel cell operation across these two different applications. Such consistency of operation offers improved reliability for both fuel cell applications, since the fuel cell can be designed to achieve optimal lifetime under one mode of operation.

This proposed strategy of leveraging simple fuel cell cycle operation with hybrid operation remains to be studied in greater detail, especially regarding plant response to safety actions. However, significant cost savings and gains in reliability will be possible if it can be shown that such a strategy is possible. It is partly the aim of this work to begin a closer investigation of such a strategy. The control strategies developed and presented use only actuators that exist in common simple cycle balance of plant. No additional actuators such as bypass valves, etc., are added to the system.

The overall control approach is similar between the NFCRC and NETL models. During a load change, the fuel flow control maintains the set-point fuel utilization to the fuel cell. The GT load adjusts to obtain the airflow rate (via GT speed) to the catalytic oxidizer to maintain a specified, maximum temperature. However, the actual implementation of the process temperature control via turbine speed control is different between the models. The NFCRC model now uses a cascade control scheme to achieve a set point MCFC operation temperature. The cascade control adjusts the set point of the GT speed to control the catalytic oxidizer temperature, which in turn maintains a constant average MCFC temperature. A diagram of the controller design is presented in Figure 5. In each controller, U is the input variable and Y is the output variable. To determine if improvements are to be seen by this new approach, the NETL model will continue to use the control scheme used in the previous work (shown in Figure 15) as a point of comparison. Finally, the performance of both models will be examined and compared over a longer time period with a larger voltage perturbation to the fuel cell at a specified ramp rate.

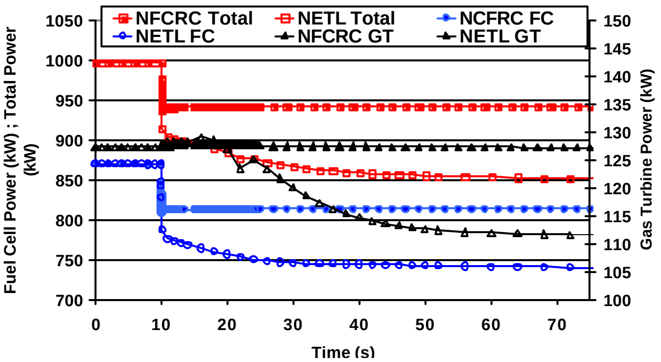

Figure 2. MCFC, GT and total power controlled system

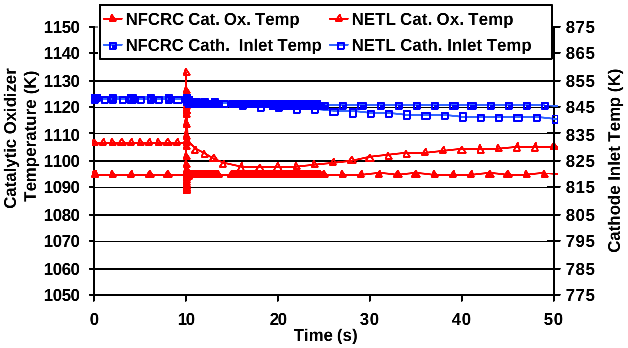

Figure 3. Catalytic oxidizer and cathode inlet temperature controlled system

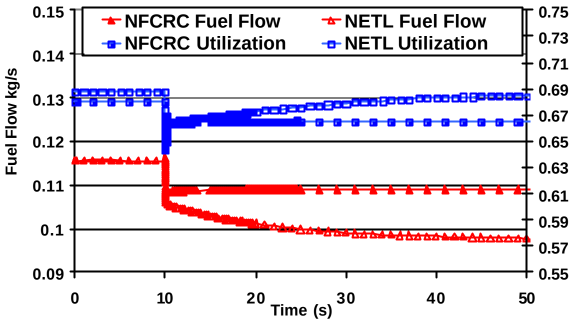

Figure 4. MCFC fuel flow and utilization controlled system

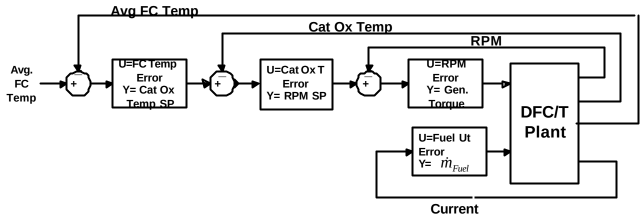

Figure 5. Cascade controller design

RESULTS

Cascaded Cathode Inlet Temperature Control

The NFCRC model simulated a ramp down in MCFC power over a 10-minute period by manipulating the MCFC operating voltage (GT power is only manipulated by the controllers in order to control the system temperatures). As the power is being ramped down, the controllers work to keep the MCFC temperature constant. Figure 7-10 present the important parameters during the load perturbation. For the ramp down in system power the goals of the control strategy were met successfully, but not without surprising results. Figure 7 presents the total, MCFC and GT power of the system. The total initial power of the system is 1 MW. The power demand from the MCFC is ramped down over a 10-minute period from 875 kW to 600 kW. As the power from the MCFC is lowered the fuel flow is lowered in order to maintain constant fuel utilization. The fuel controller is the only p-type controller in the system. It measures the current being produced from the MCFC and proportionally gauges the fuel flow according to Faradays Law. Figure 8 presents the MCFC fuel utilization and the fuel flow entering the MCFC. The fuel utilization is maintained fairly constant as the power is being ramped down. The fuel flow follows a proportional slope to the MCFC power. The MCFC power does recover slightly causing the fuel flow to increase in order to maintain constant fuel utilization. This recovering in power results from the actual manipulation of the MCFC voltage to change the power instead of changing the power demand itself.

Lowering power demand on the MCFC decreases the amount of fuel entering the catalytic oxidizer thus lowering the catalytic oxidizer temperature. To counteract the lowering catalytic oxidizer temperature, the GT power is ramped up to reduce the turbine speed thus lowering the mass flow entering the system. The GT power is increased from 127 kW to initially peak output at 180 kW. The GT power oscillates as the controllers change the generator load on the GT. The GT power does not settle down until after the 10-minute MCFC load change. The gains on the controllers are not optimized, causing the unsteady oscillations to occur in the GT load. The reduction of turbine speed and compressor mass flow is illustrated in Figure 10. As the compressor mass flow is lowered the gas composition entering the MCFC changes.

Unique to the MCFC is the feedback cycle on CO_2. An increase in CO_2 in the cathode gas stream increases the Nernst potential. As the compressor mass flow is decreased the mole fraction of CO_2 increases, while the mole fraction of N_2 and O_2 decreases. Ideally one would want to operate the MCFC with 2/3 CO_2 and 1/3 O_2 for the cathode molar composition. With the increase of CO_2 mole fraction in the cathode steam, the MCFC power increases around 50kW. Figure 10 presents the increase in Nernst potential as the compressor mass flow is changing.

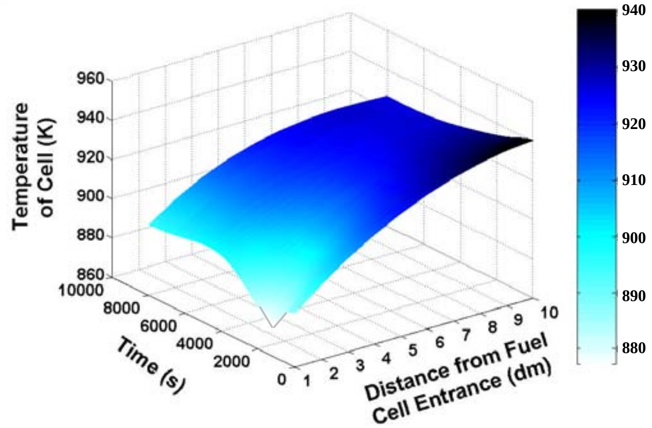

Figure 6. MCFC temperature profile

It was expected that the GT power would increase in order to reduce the turbine speed, but eventually return to a lower power output once a new mass flow and thermal equilibrium was reached. Instead, the GT power increases and remains at higher power output even though there is less fuel or raw energy entering the system. With the increase in GT power and MCFC power production there is an increase in overall system efficiency as shown in Figure 8. In fact there is a substantial increase in system efficiency of 10%. This increase in system performance comes, however, with a new concern. In order to maintain a constant average temperature in the MCFC, the cathode inlet temperature must remain fairly constant. In the case of lower power demand the cathode inlet temperature must increase slightly to counteract the decrease in heat being generated in the MCFC.

To increase the cathode inlet temperature, the catalytic oxidizer temperature is increased. In Figure 9 the cathode inlet temperature increases only about 5ºC. Yet, to increase the cathode temperature just 5ºC the catalytic oxidizer temperature increased 120ºC. The catalytic oxidizer temperature peaked at 1265 K, which could potentially damage hardware. The significant increase in the catalytic oxidizer temperature (i.e., the hot-side inlet to the heat exchanger) occurs due to the increase in temperature difference between the two gas streams, which increased the heat being transferred from the hot stream to the cold stream in the heat exchanger. This resulted in the energy that was intended to remain in the hot stream (eventually the cathode inlet) to actually be transferred to the cold stream. In fact because of the lower flows and increased temperature difference between the two streams, the effectiveness of the recuperator increased from 82% to 92% as seen in Figure 7, which increases the difficulty.

The MCFC average temperature was maintained, but the temperature profile was not. It was expected that the temperature difference across the MCFC would increase since the mass flow was significantly reduced when proportionally compared to the MCFC power drop. However, the temperature profile improves as a lower temperature change across the MCFC is seen. The change in the temperature profile is illustrated in Figure 6.

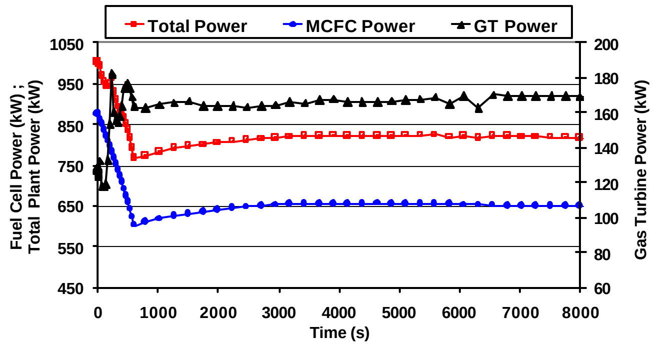

Figure 7. NFCRC system power after a controlled load drop on the MCFC

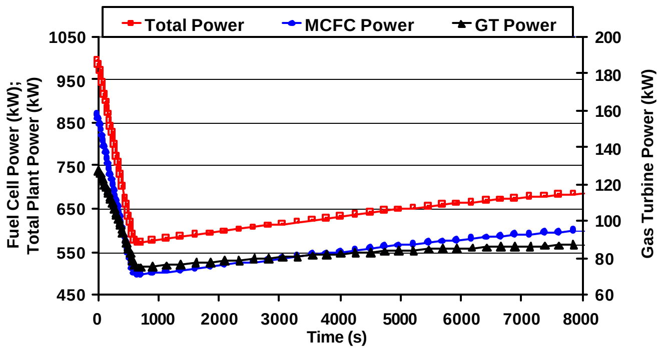

Figure 11. NETL system power after controlled load drop on the MCFC

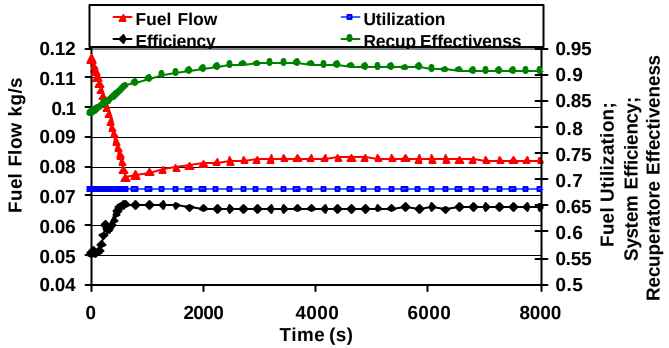

Figure 8. NFCRC fuel flow, utilization, system efficiency and recuperator effectiveness

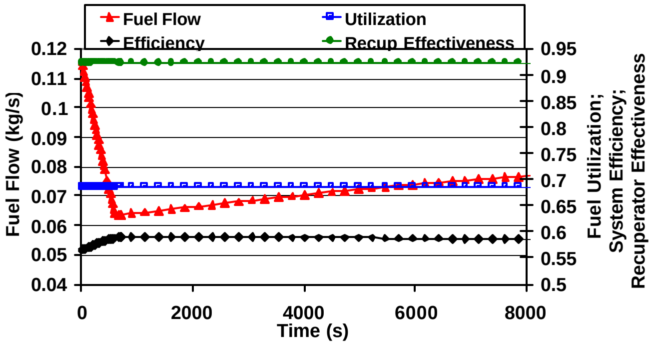

Figure 12. NETL fuel flow, fuel utilization, system efficiency and recuperator effectiveness

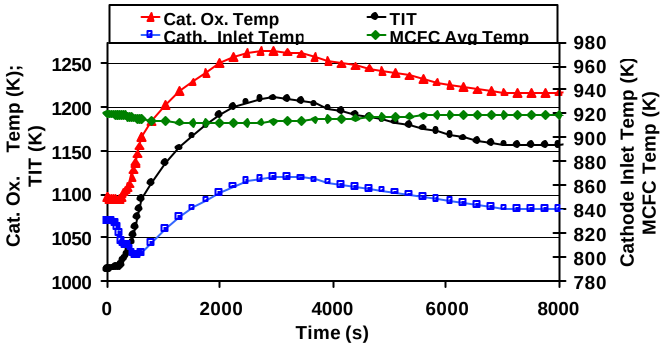

Figure 9. NFCRC MCFC, catalytic oxidizer, cathode inlet and turbine inlet temperature

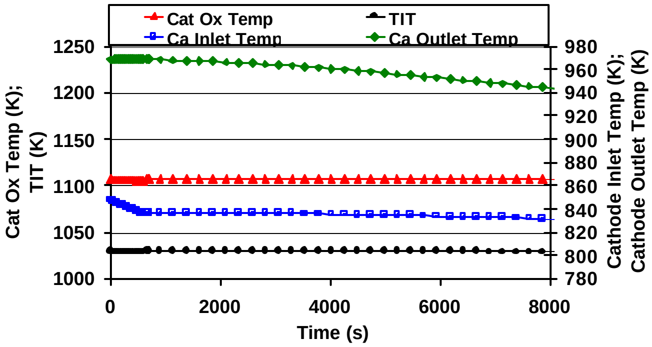

Figure 13. NETL cathode inlet, cathode exit, catalytic oxidizer, and turbine inlet temperature

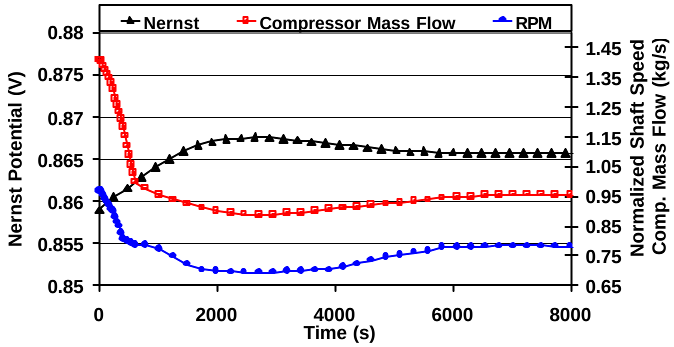

Figure 10. NFCRC compressor mass flow, shaft speed and Nernst potential

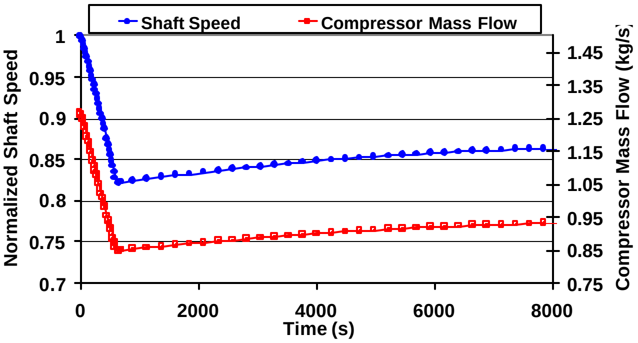

Figure 14. NETL compressor mass flow and RPM

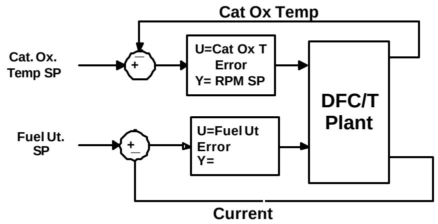

Figure 15. Catalytic oxidizer control scheme

Even though the MCFC temperature was successfully maintained and there was an improvement in the temperature gradient, there was only a 19-20% decrease in plant power. The system is operating at excessive temperatures for the catalytic oxidizer, recuperator, and possibly the TIT. The current control strategy will have to be altered in order to achieve safe and efficient operation at lower power plant load demands. Perhaps there is a temperature range at which the MCFC can operate safely and efficiently. Identifying an operating range for the MCFC temperature will provide flexibility in the operation of the MCFC/GT. The average MCFC temperature set point could be adjusted within this temperature range depending on the optimal point of operation for a particular load.

Catalytic Oxidizer Temperature Control

In comparison, the NETL model, having a different control method, shows very different results. It is interesting that while the NETL MCFC power shown in Figure 11 is 100kW lower than NFCRC's after the ramp, it slowly recovers and it appears that it may approach a similar value (650kW). The NETL model takes a much longer time to come to equilibrium. The following explanation is given. For both models, when a voltage perturbation is made to the fuel cell there is a change in the current profile and thus change in hydrogen composition profile. The temperature profile will then slowly change, being driven by the new current and hydrogen concentration distribution. How fast this happens will depend on not only the thermal capacitance of the fuel cell, but on how closely the new profiles are to their future equilibrium profile values. So, while there could be two fuel cells that have similar steady state point values, their transient characteristics could be quite different for different control methods. One significant difference between the fuel cell models is that the NFCRC model reforms approximately 30% of its fuel in the anode passage. For the NETL, model the reforming is all indirect internal; that is, it is fully reformed in a separate passage prior to entering the fuel cell anode passage. Therefore it is not unexpected that they should have different profile characteristics. Unfortunately, the NETL fuel cell profile data is not currently being recorded so it cannot be compared to the NFCRC model. Future runs will record this data.

Before the perturbation, the NETL fuel cell is operating about 20K higher than the NFCRC fuel cell (940K compared to 920K). In Figure 14, the NETL model has less cooling air (1.27 vs. 1.35 kg/s from the NFCRC model), which may account for the higher temperature. While the NFCRC control model maintains the fuel cell temperature by adjusting the catalytic oxidizer set point temperature, the NETL model keeps the same set point. While the airflow has been reduced in order to reduce cooling gas to the fuel cell following the reduction in MCFC power, the reduction was not enough to prevent cooling of the MCFC. Both the cathode inlet and outlet temperatures are decreasing as seen in Figure 13. The fact that the cathode outlet temperature is decreasing at a greater rate than the cathode inlet temperature shows that there could be too much cooling flow. A lower temperature difference across the fuel cell would appear desirable. However, having a lower cathode outlet temperature will lead eventually to lowering the cathode inlet temperature through the heat exchange process, thus the overall fuel cell temperature will continue to decrease. The NETL model started at a somewhat high temperature for a typical MCFC, so the temperature decreases were not so detrimental; however, it is more likely that the starting operating temperatures will be lower, more in line with the NFCRC model conditions.

CONCLUSION

Two different control strategies were presented and provided very different results. The cascade control design implemented by NFCRC was successful in controlling the MCFC temperature and performed beyond expectations with respect to the temperature gradient across the fuel cell and the system efficiency. The drawback is the catalytic oxidizer temperature reached excessive temperatures, which could potentially damage the recuperator and catalytic oxidizer depending on the catalyst and metals used. Also, the controller gains need to be investigated further with the anticipation of reducing or eliminating oscillations in GT power. The NFCRC results also point out the non-linear characteristics of the hybrid system. For example, the catalytic oxidizer temperature was increased 120ºC in order to achieve a 5ºC increase in cathode inlet temperature. The TIT was increased which accomplished another goal of maximizing the TIT while controlling the MCFC temperature.

NETL results successfully controlled the fuel utilization and the catalytic oxidizer temperature. The primary concern identified with this approach is the overall decrease in gas temperature entering and leaving the fuel cell cathode. There are two potential solutions offered here to remedy this problem.

The first involves increasing the fuel utilization set-point of the fuel cell, as maintained by controlling the fuel flow, which would decrease in this scenario. (Note, this would go against the initial goal to keep the fuel utilization constant as discussed in the Approach section of this paper.) The heat content of the fuel cell gas streams would be higher since more heat would be generated by the fuel cell and less heat would be required for the internal fuel reforming. Also, because the amount of spent fuel to the catalytic oxidizer would be less, the airflow rate would decrease since the catalytic oxidizer would be trying to maintain its set point temperature. Thus, cooling flow through the cathode would be reduced. If controlled, the utilization should not become so high that the fuel cell would be adversely impacted. The second solution would be a bypass around the fuel cell cathode. However, this would require additional equipment and complexity that is trying to be avoided.

Both the NFCRC and NETL control strategies safely controlled the hybrid system provided proper thermal design of various system components. In order to adequately test and ensure the control strategies maintain safe and efficient operation, operation limits of system components need to be identified and the controls modified to account for such additional constraints. For example, the maximum inlet temperature of the recuperator, GT, and the catalyst in the catalytic oxidizer must be identified and designed into the controls. Also a range of operating temperatures and temperature gradients for the MCFC must also be known so that a safer and more optimal range of set points can be chosen to improve the performance of the MCFC and the rest of the system. Such design studies will be the subject of future work.

The current studies investigate the dynamics and the limits of the proposed control schemes have on controlling the desired parameters, which is necessary in achieving the goal of developing a control scheme that would provide safe and efficient operation of a load following FC/GT system. As proposed for future work these preliminary studies need to continue in order to establish the needed balance of plant that would provide the required range of power demanded by the grid.

REFERENCES

1. Veyo S E, Lundberg W L, Vora S D, and Litzinger K P, *Tubular SOFC Hybrid Power System Status*. Preceedings of ASME Turbo Expo 2003, 2003. **GT2003-38943**.

2. Ghezel-Ayagh H, Daly J M, and Wang Z-H. *Advances in Direct Fuel Cell / Gas Turbine Power Plants*. in *2003 ASME Turbo Expo, Atlanta, Georgia*. 2003.

3. Bessette N F, *Modeling and Simulation for SOFC Power Systems*, in *Mechanical Engineering*. 1994, Georgia Institute of Technology: Atlanta. p. 209.

4. Costamagna P, Magistri L, and Massardo A F, *Design and Part-Load Performance of a Hybrid System Based on a Solid Oxide Fuel Cell Reactor and a Micro gas Turbine*. Journal of Power Sources, 2000. **96**: p. 352-368.

5. Costamagna P, Selimovic, Azra, Borghi, Marco Del, Agnew, Gerry, *Electrochemical Model of the Integrated Planer Solid Oxide Fuel Cell (IP-SOFC)*. Chemical Engineering Journal, 2004. **102**: p. 61-69.

6. Massardo A F and Lubelli F, *Internal Reforming Solid Oxide Fuel Cell-Gas Turbine Combined Cycles (IRSOFC-GT):Part A- Cell Model and Cycle Thermodynamic Analysis*. Journal of Engineering for Gas Turbines and Power, 2000. **122**: p. 27-35.

7. Rao A D and Samuelsen G S, *Analysis Strategies for Tubular Solid Oxide Fuel Cell Based Hybrid*. Journal of Engineering for Gas Turbines and Power, 2002. **124**(July 2002): p. 503-509.

8. Yi Y, Smith T P, Brouwer J, and Rao A D, *Simulation of a 220 kW Hybrid SOFC Gas Turbine System and Data Comparison*. 2003.

9. Gemmen R S, et al., *Development of Dynamic Modeling Tools for Solid Oxide and Molten Carbonate Hybrid Fuel Cell Gas Turbine Systems*. 2000 ASME Turbo Expo, Munich, Germany, 2000. **2000-GT-0554**.

10. Migistri L, et al., *Transient Analysis of Solid Oxide Fuel Cell Hybrids. Part C: Whole Cycle Model*, in *ASME Turbo Expo, Vienna, Austria*. 2004.

11. Liese E A, Gemmen R S, Jabbari F, and Brouwer J, *Technical Development Issues and Dynamic Modeling of Gas Turbine and Fuel Cell Hybrid Systems*. Journal of Engineering for Gas Turbines and Power, 1999.

12. Liese E A, Gemmen, Randall S., *Dynamic Modeling Results of a 1 MW Molten Carbonate Fuel Cell/Gas Turbine Power System*. 2002 ASME Turbo Expo, Amsterdam, The Netherlands, 2002. **GT-2002-30110**.

13. Lukas M D, Lee K Y, and Ghezel-Ayagh H, *Development of a Stack Simulation Model for Control Study on Direct Reforming Molten Carbonate Fuel Cell power Plant*. IEEE Transactions on Energy Conversion, 1999. **PE-468-EC-0-01-1999**.

14. Lukas M D, Lee, Kwang Y., Ghezel-Ayagh, Hossein, *Operation and Control of Direct Reforming Fuel Cell Power Plant*. IEEE Power Engineering Society, 2000.

15. Roberts R A, Brouwer J, Gemmen R, and Liese E, *Inter-Laboratory Dynamic Modeling of a Carbonate Fuel Cell for Hybrid Application*. 2003 ASME Turbo Expo, Atlanta, Georgia, 2003. **GT2003-38774**.

16. Roberts R A, Brouwer J, Gemmen R, and Liese E, *Dynamic Simulation of Carbonate Fuel Cell-Gas Turbine Hybrid Systems*. ASME Turbo Expo, Vienna, Austria, 2004. **GT2004-53653**.