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DYNAMIC SIMULATION OF CARBONATE FUEL CELL-GAS TURBINE HYBRID SYSTEMS

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ABSTRACT

Hybrid fuel cell/gas turbine systems provide an efficient means of producing electricity from fossil fuels with ultra low emissions. However, there are many significant challenges involved in integrating the fuel cell with the gas turbine and other components of this type of system. The fuel cell and the gas turbine must maintain efficient operation and electricity production while protecting equipment during perturbations that may occur when the system is connected to the utility grid or in stand-alone mode. This paper presents recent dynamic simulation results from two laboratories focused on developing tools to aid in the design and dynamic analyses of hybrid fuel cell systems. The simulation results present the response of a carbonate fuel cell/gas turbine, or molten carbonate fuel cell/gas turbine, (MCFC/GT) hybrid system to a load demand perturbation. Initial results suggest that creative control strategies will be needed to ensure a flexible system with wide turndown and robust dynamic operation

NOMENCLATURE

A_{surf}	Surface area
E_a	Activation Energy
K_j	Equilibrium Constant for concentrations
K_{pi}	Equilibrium Constant for partial pressures
k_i	Rate constants from the Arrhenius equation
K_o	Pre-exponential for the Arrhenius equation
K''	Pre-exponential per unit area
R_i	Dynamic reaction rates [kmol/sec] for reaction i
C_j	Concentrations of species j
y	Change in kmoles for water-gas shift reaction

INTRODUCTION

Fuel cell systems provide promise for more efficient and environmentally friendly energy production. Certain classes of "high temperature" fuel cells are capable of using hydrocarbon fuel as long as the system contains a reformer that can process the fuel to create a hydrogen/carbon-monoxide rich mixture. This capability allows fuel cells to

use renewable (biomass) as well as fossil fuels. For large-scale high temperature fuel cells, one can also use the high quality exhaust heat for various purposes such as thermal energy for industrial processes, chemical recuperation (reformation) using the fuel supply, or cogeneration of electricity via a gas or steam turbine, as is the case with a hybrid fuel cell/gas turbine (FC/GT) cycle.

In FC/GT hybrid systems, it is very important to properly match and integrate the fuel cell with the gas turbine portions of the cycle. Too little mass flow in the cathode could lead to overheating of the fuel cell. At the same time, too much mass flow could lower the turbine inlet temperature (TIT) of the gas turbine leading to efficiency decreases, performance degradation, and even gas turbine shut-down. A complete shutdown of the turbine can be damaging to the fuel cell and other system components. In the case of a carbonate fuel cell (or molten carbonate fuel cell, MCFC), the operating temperature is generally desired to be around 650°C. This operating temperature is good for reformation and processing of the original hydrocarbon fuel, but at the same time this temperature is too low for a typical gas turbine TIT. As a result, MCFC/GT hybrid systems generally consist of a fuel cell operating with sufficient excess fuel followed by oxidation of the excess fuel emitted from the anode so as to raise the turbine inlet temperature. This approach can produce very high TIT but at the expense of the overall system fuel-to-electrical efficiency. The fuel cell is the most efficient part of the power plant. So, utilizing as much fuel as possible in the fuel cell (without hindering the performance of the fuel cell) while concurrently maintaining good gas turbine performance is the goal.

The MCFC can handle higher fuel utilizations than what is needed to maintain an acceptable TIT. As a result, there is some design parameters that should allow control even under dynamic conditions. One additional parameter that can be manipulated in the design of an MCFC/GT hybrid system is the mass flow rate through the compressor and therefore the fuel cell. However, when the mass flow is lowered such operation could lead to over heating of the MCFC.

The MCFC requires that the heat being generated within the stack be carried off by the anode and cathode gas in order to maintain an optimal temperature. On the other hand, one could design the fuel cell module to directly use a portion of this heat by incorporating internal reformation in the MCFC stack design.

Internal reformation involves endothermic reactions that can absorb the heat directly where it is being generated by the electrochemical reactions. Use of internal reformation provides an additional means of cooling the MCFC, and results in decreased cathode mass flow cooling requirements for the MCFC. As a result, internal reformation increases system efficiency by reducing thermal loss and increasing TIT, and it reduces cost through reduction of heat exchanger requirements [1]. In addition, this approach should provide a more robust hybrid performance envelope. However, it also produces a quicker responding cooling effect due to the immediate proximity of the endothermic reforming action to the stack. Such quick response times need to be carefully considered in the design of the control system, and in the operation of the hybrid system,

Once these overall design decisions are set, control strategies must be employed that can maintain the proper temperatures throughout the MCFC/GT power plant. This needs to be done in order to achieve efficient, safe, and reliable operation during perturbations (e.g., load changes) that may be imposed on the system. The dynamic simulation capabilities developed at National Fuel Cell Research Center (NFCRC) and National Energy Technology Laboratory (NETL) and presented herein are useful for: (1) determining design requirements, (2) analyzing dynamic response, and (3) developing control strategies for MCFC/GT hybrid systems.

Work has been done by others to find the optimal design of different types of fuel cell-gas turbine hybrids. To analyze the performance of hybrid system design, research groups have developed steady-state models to analyze the design and off-design performance of various fuel cell-gas turbine hybrid systems [2], [3].

APPROACH

This paper presents the development and comparison of two dynamic MCFC/GT models. The two models have similar features in their thermodynamic approach to simulating a MCFC/GT hybrid. The NETL model uses C++ in combination with the ProTRAX software package. The NFCRC is constructed in Simulink™ software package. The respective solution strategies for determining dynamic hybrid system performance vary according to the software packages used by the parties.

The details of the MCFC and gas turbine simulation approach have been presented and discussed in previous papers [4], [5], [6], [7]. Suffice it to note that identical assumptions are made in formulating the set of governing equations for the fuel cell models, which includes discretized solution of the Nernst equation, all major electrochemical losses (polarizations), mass conservation, energy conservation and heat transfer processes. Similar solution strategies are employed for all components, but, slightly different compressor and turbine maps are used, and a significantly

different approach to simulating heat exchangers is employed by the two parties. Each of these models, however, retains an appropriate dependence upon heat exchanger design and operating conditions through non-dimensional numbers (e.g., Reynolds, Nusselt, Prandtl).

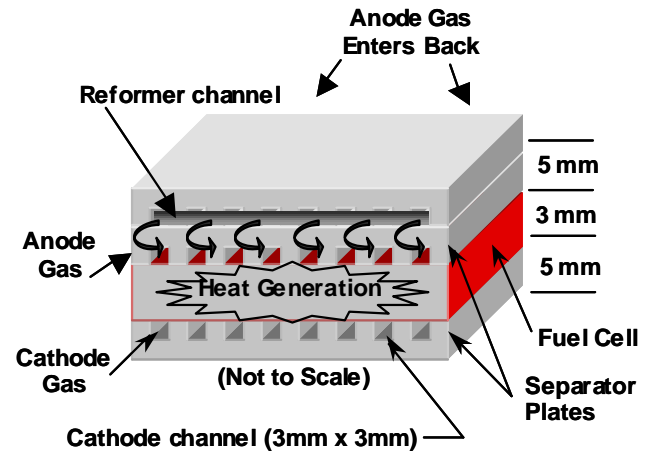


Figure 1. MCFC Diagram

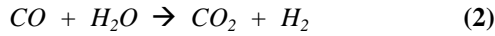
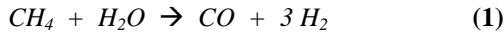
CARBONATE FUEL CELL MODEL

Each of the MCFC models is constructed to simulate the fundamental operation of a MCFC similar to that currently manufactured by FuelCell Energy, Inc. Results from NFCRC and NETL fuel cell models are compared under the same operating conditions, with analysis based on a 1.08 m², single cell, co-flow, planar fuel cell with prescribed anode and cathode inputs.

A partially reformed anode gas and cathode gas mixture representative of that which characterizes the FuelCell Energy, Inc. system was used for comparison of the fuel cell models [1]. The anode gas was modeled entering a reformation channel (part of the separator plate) in counter-flow with the internal cathode and anode gas flows. Figure 1 illustrates this process. The anode gas is preheated and pre-reformed in the reformation channel. It was found that by creating this counter flow in-stack reformer and having the reformation begin where the anode and cathode gases exit, the temperature profile in the fuel cell is more uniform. If the pre-reformation channel were not present in the geometrical configuration of the model then most of the methane would reform near the entrance of the MCFC anode compartment. This would cause a dramatic cooling effect and create a large temperature gradient through the cell. This large gradient would hinder the electrochemical performance, lead to mechanical stresses, and possibly cause premature deterioration of the cell materials.

Modeling of the Internal Reformation

The capability of simulating internal reformation of the type described above is a major advancement of the model that is presented first in this paper. The internal reformation model is broken into two concurrent steps, steam reformation of methane and water gas shift.



The rate of the steam reformation step is determined by a dynamic Arrhenius rate expression and the water gas shift is assumed to be in equilibrium. The reformation model uses rates that are consistent with the use of typical nickel-based catalysts. The equilibrium constant for equation (1) is determined from the following curve fit [8],

$$K_{P_{ref}} = 1.198 E + 17 * e^{\frac{-26830}{T}} \quad (3)$$

To convert this from partial pressure parameters to concentration parameters the following equation is used

$$K_{ref} = \frac{K_{P_{ref}}}{(R_u * T)^2} \quad (4)$$

The pre-exponential term of equation (3) [8] is scaled by the catalytic surface area as follows

$$K_o = A_{surf} K^n \quad (5)$$

The forward reformation reaction rate constant is determined by the following expression:

$$k_{forward} = K_o * (R_u * T)^{(a+b)} * e^{\frac{-E_a}{R_u T}} \quad (6)$$

where

$$E_a = \text{activation energy (23000 [kJ/kmol])},$$

$$a = 1, \text{ and}$$

$$b = -1.25.$$

The forward reaction rate for the reformation is:

$$R_{Forward} = C_{CH_4}^a * C_{H_2O}^b * k_{forward} \quad (7)$$

In the current internal reformation model the rate of the reverse reformation reaction (i.e., reverse rate of reaction (1)) is determined through the equilibrium constant as:

$$k_{reverse} = \frac{k_{forward}}{K_{ref}} \quad (8)$$

The reverse reaction rate is determined from the following

$$R_{reverse} = C_{CO} * C_{H_2}^3 * k_{reverse} \quad (9)$$

The result of water gas shift chemistry, which is assumed to be in equilibrium, is determined by calculating the equilibrium constant using Equation 10 and solving the quadratic in Equation 11, [8].

$$K_p = 1.767E - 2 * e^{4400/T} \quad (10)$$

$$(1 - K_p)y^2 + [C_{H_2} + C_{CO_2} + K_p * (C_{CO} + C_{H_2O})]y + (C_{H_2} * C_{CO_2} - K_p * C_{CO} * C_{H_2O}) = 0 \quad (11)$$

Where y is net the change in moles, which can be used in the following equations.

$$C_{H_2} = C_{H_2 \text{ in}} + y$$

$$C_{CO_2} = C_{CO_2 \text{ in}} + y \quad (12)$$

$$C_{CO} = C_{CO \text{ in}} - y$$

$$C_{H_2O} = C_{H_2O \text{ in}} - y$$

The CO is assumed to be consumed/created in the fuel cell by only water gas shift chemistry. Direct electrochemical oxidation of CO and hydrocarbons is neglected, which has been shown experimentally to be a reasonable assumption [9].

Fuel Cell Model Comparisons

The MCFC geometry and dynamic response of a laboratory scale MCFC model were presented in a previous paper [7] along with the dynamic equations used in each of the models. The same MCFC models are used in the comparison presented in this paper. The most significant change in the models is the addition of internal reformation simulation capabilities.

Table 1 presents the parameters used in the current model. The two models were simulated with partially reformed gas entering the MCFC anode. The values are compared to ensure that predicted performance matches closely. The comparison of steady state results are presented in Table 2. The voltages of the models were held constant at 0.7 V. The models compare very well with regard to predictions of exit species concentrations, current production, and overall fuel and oxidant utilization.

MCFC/GT HYBRID MODEL

The MCFC/GT models have similar features and have the FuelCell Energy, Inc. configuration of a Direct FuelCell/Turbine® (DFC/T®) sub-MW system. A diagram of the system is presented in Figure 2. The fuel heater is slightly different than the DFC/T power plant presented by FuelCell Energy, Inc. [10].

Gas Turbine Model

The small gas turbine (or micro-turbine) simulated in this paper contains a single stage radial compressor and expander connected on the same shaft to a generator. Generic radial turbine and compressor maps are used to establish compressor and turbine performance over a wide range of operation. The NFCRC gas turbine model has a pressure ratio of 3:1. The design parameters for the gas turbine are provided in Table 3. NETL's gas turbine model is slightly different. At steady state, the compressor pressure ratio is 4:1. The turbine inlet temperature is 785°C. The design parameters and the turbine and compressor maps used by NETL are based upon measured performance of a small gas turbine engine.

Table 1. Fuel cell parameters for comparison

Parameter	Unit	Value
Number of Channels		216
Cell Active Area	m ²	1.08
Anode Specification		
Inlet Temperature	K	923
Inlet Pressure	Pa	104425.2
Exit Pressure	Pa	104425.2
Channel Width	m	0.0031
Channel Height	m	0.0013
Inlet CH ₄	mole frac	0.2798
Inlet CO	mole frac	0.005
Inlet CO ₂	mole frac	0.0346
Inlet H ₂	mole frac	0.1168
Inlet H ₂ O	mole frac	0.5662
Cathode Specification		
Inlet Temperature	K	923
Inlet Pressure	Pa	104425.2
Exit Pressure	Pa	104425.2
Inlet CO ₂	mole frac	0.1553
Inlet H ₂ O	mole frac	0.1553
Inlet N ₂	mole frac	0.559
Inlet O ₂	mole frac	0.1294
Channel Width	m	0.0031
Channel Height	m	0.0032
Exchange Current Density	amp/m ²	50
Diffusion Limiting Current Density	amp/m ²	4000
Transfer Coefficient		0.75
Cell Specification		
Thickness	m	0.01
Heat Capacity	J/kg-K	800
Density	kg/m ³	1500
Net Resistance	ohm-m ²	$-6.667 \times 10^{-7} (T-273) + 4.7833 \times 10^{-4} / A_{cell}$
Separator Specification		
Thickness	m	0.001
Heat Capacity	J/kg-K	611
Density	kg/m ³	7900

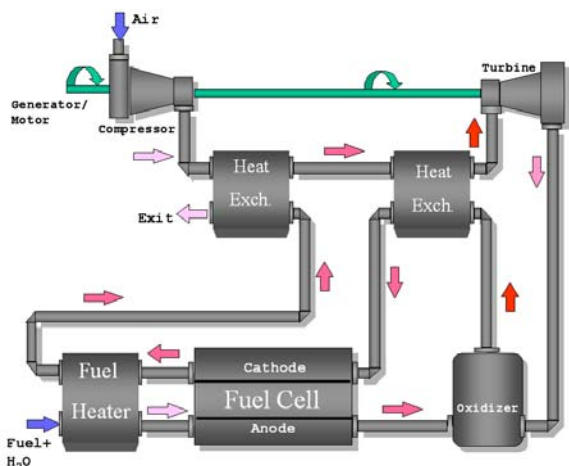


Figure 2. MCFC/GT hybrid power plant schematic

The dynamic response of the gas turbine engine models is based upon solution of a dynamic expression that governs shaft speed, which balances compressor and generator loads and gas turbine inertia with power produced in the turbine. The compressor plenum volume (note, the NETL model does not contain a plenum volume) provides for mass storage in the system. The mass flow presented in Table 4 is higher than what today's micro-turbines can provide, but is not unrealistic to expect from emerging turbo-machinery designed for hybrid systems applications. With these design parameters, the micro-turbine produces about 10% of the total hybrid system power at the design point.

1-D Heat Exchanger Model

NETL's heat exchanger models simulate a state-of-the-art primary surface type heat exchanger following McDonald [11]. It is modeled in one dimension with 3 nodes. The NFCRC heat exchanger models assume a flat plate design, which are simulated using first principals (i.e., concurrent solution of the momentum, convection and conduction equations in a shell and tube geometry as a function of heat exchanger length). It resolves one dimension of the heat exchangers in discrete lumped parameter cells. As a basis for comparison, both models are assumed to have the same thermal capacitance. The following assumptions for heat exchanger masses were made: the high temperature heat exchanger has a mass of 400 kg, the steam generator and fuel heater section has a mass of 250 kg, and the low temperature heat exchanger has a mass of 300 kg.

Catalytic Oxidizer Model

The catalytic oxidizer model of both NETL and NFCRC completely oxidizes all of the remaining fuel from the fuel cell anode gas stream. The adiabatic flame temperature is calculated for the combined anode/gas turbine exhaust gas mixture. The catalytic oxidizer is assumed to have no mass, therefore there is no thermal capacitance associated with the catalytic oxidizer in either model.

MCFC/GT HYBRID DYNAMIC SIMULATION RESULTS

The NETL and NFCRC integrated hybrid systems models were each run with the same set of inlet conditions and operating parameters. This was done to establish that both models produce similar steady-state results under the same conditions. The steady-state results from both the NETL and NFCRC hybrid system models for these conditions are presented in Table 4. The majority of the steady state performance comparisons presented in Table 4 suggests a relatively similar predicted performance for the hybrid system. There is a disparity between the cathode inlet temperature and the MCFC stack power predictions of the two models, which is probably due to the differences in the heat exchanger simulations.

Table 2. Steady-state results for the MCFC with internal reformation

Parameter	Unit	NFCRC	NETL
Anode			
<i>Outlet</i>			
Outlet Temperature	K	923	923
Outlet CH ₄	mole frac	0.0007	0
Outlet CO	mole frac	0.00133	0
Outlet CO ₂	mole frac	0.499	0.4922
Outlet H ₂	mole frac	0.1195	0.1417
Outlet H ₂ O	mole frac	0.3794	0.366
Cathode			
<i>Outlet</i>			
Outlet Temperature	K	923	923
Outlet CO ₂	mole frac	0.0739	0.0629
Outlet H ₂ O	mole frac	0.18	0.1833
Outlet N ₂	mole frac	0.648	0.66
Outlet O ₂	mole frac	0.09695	0.0925
Cell			
Voltage	V	0.7	0.7
Current	A	1216	1212
Fuel Utilization		75.10%	74.37%
Oxygen Utilization		35.34%	40.70%

Table 3. Gas turbine parameters

Design Spec	Value
Design Mass Flow Rate (kg/sec)	1.33
Design Turbine Inlet Pressure for NFCRC (kPa)	304
Design Turbine Inlet Pressure for NETL (kPa)	405
Design Turbine Inlet Temperature (K)	1050
Design Compressor Inlet Pressure (kPa)	101.325
Compressor Impeller Radius (m)	0.055
Design Compressor Inlet Temperature (K)	298
Design Speed (RPM)	65000
Diffuser Expansion Ratio	1.4
Plenum Volume (NFCRC only) (m ³)	0.8

Table 4. Steady-state hybrid results

Description	NFCRC	NETL
Catalytic Exhaust Temp (K)	1129.44	1106.724
Cathode Inlet Temp (K)	856.45	847.77
Gas Turbine Power (kW)	136.35	127.32
Fuel Cell Power (kW)	856.95	869.287
Efficiency	56.20%	56.50%
Current (single cell) (A)	1025.06	1039
Voltage (single cell) (V)	0.76	0.76

Once the steady-state results were verified to be similar, each of the dynamic models was subjected to the same perturbation. The perturbation was a drop in overall load demanded from the fuel cell, which was accomplished by applying an increase in fuel cell operating voltage of 0.01V from 0.76 V to 0.77 V.

Hybrid Dynamic "Open Loop" Response

This section of the paper presents the predicted open loop system dynamics, since MCFC voltage was the manipulated variable and no other system operating parameter was controlled in these simulations. The fuel flow rate was held constant. Figures 3-5 present several hybrid system responses produced by each model during the voltage perturbation described above. When the voltage is increased, both the current of the MCFC and efficiency drop as expected. Figure 3 presents the current change and the change of the overall efficiency for each of the hybrid systems simulations (that of NETL and that of NFCRC). A difference in the current predictions is presented, which leads to a slightly higher efficiency for the NETL hybrid model (not significant). Before the perturbation, the current in both models is different, partly because of the different temperatures in the MCFC component of each model and different gas compositions through the MCFC stack that result from differences in internal reforming. The NFCRC fuel cell ends up operating at a lower temperature. This increases the internal resistance of the fuel cell, which decreases the current density of the fuel cell as well.

Figure 4 presents the catalytic oxidizer and cathode inlet temperature open loop response for the same fuel cell load perturbation. Note that the time scales associated with the dynamic response of the catalytic oxidizer and cathode inlet temperatures predicted by the two models compare well. In addition, the magnitude of the predicted final catalytic oxidizer temperature of the two models compares well. The difference in the magnitude of catalytic oxidizer temperature is about 30K before the perturbation. This is due to more fuel being available in the anode off gas in the NFCRC model because of the lower current production. After the perturbation, the catalytic oxidizers reach the same temperatures because the MCFC currents are the same after the perturbation, which is seen in Figure 3.

The increase in catalytic oxidizer temperature could be detrimental to the heat exchanger and the increase in cathode inlet temperature as seen in Figure 4 could overheat the MCFC. This increase in cathode inlet temperature could possibly be controlled by decreasing the amount fuel flow entering the MCFC or by increasing the air mass flow through the MCFC.

Figure 5 presents the change in the total MCFC/GT hybrid system power and the MCFC and gas turbine power for both hybrid system models. For the open loop system, both hybrid models predict that the MCFC power drops followed by a rise in gas turbine power due to a rise in catalytic oxidizer temperature. Although the magnitudes of power predicted by the respective models are not the same, the time scales associated with the dynamic response of the hybrid system are well matched. The fuel cell fairly rapidly drops in power output (order of 10 seconds), followed by a gas turbine response that endures longer than the 50 seconds plotted in Figure 5. Since the heat exchangers are modeled with small masses in this case, the gas turbine power rises fairly quickly and the total power of the system does recover slightly due to the increase in gas turbine power.

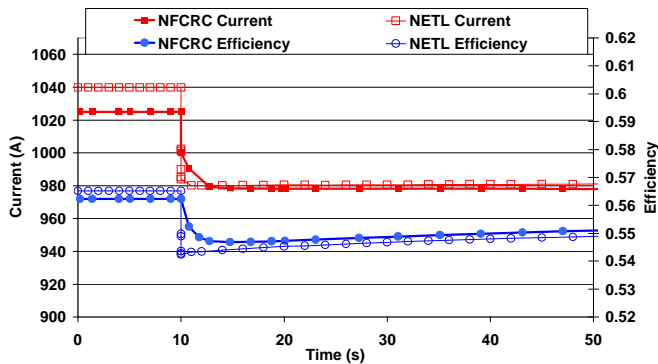


Figure 3. 1.08 m2 Fuel cell response and overall hybrid efficiency during an increase of fuel cell voltage 0.76V → 0.77V for an open loop system

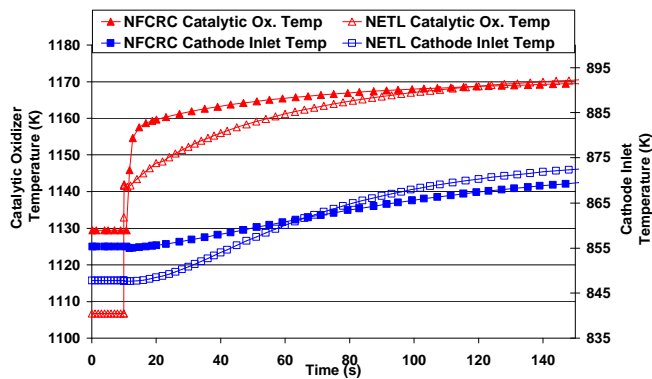


Figure 4. Catalytic oxidizer and cathode inlet temperature during an increase of fuel cell voltage 0.76V → 0.77V for an open loop system

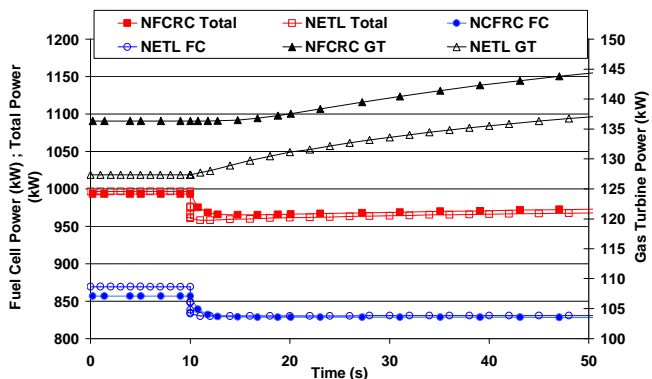


Figure 5. Power of fuel cell and gas turbine during an increase of fuel cell voltage 0.76V → 0.77V for an open loop system

Hybrid System Control Strategies

In order to minimize the thermal impact on the fuel cell, it is desirable to maintain a fairly constant inlet temperature to the cathode. This can be done in various ways. One method adjusts the turbine speed to adjust airflow to the oxidizer, changing the temperature in the oxidizer and ultimately the temperature at the cathode inlet. The generator load is adjusted in order to maintain the desired turbine shaft

speed. The controller would likely use the catalytic oxidizer temperature as the controlled parameter since response of the cathode inlet temperature would be impacted by the thermal mass of the high temperature heat exchanger. However, the present case presents a turbine that starts out at 100% speed. Since increases in turbine speed are not allowed at this point, the oxidizer temperature cannot be controlled by increasing turbine speed. As a result the NETL model allows additional adjustment of fuel flow to maintain the original fuel utilization. A decrease in load demand to the fuel cell will require a decrease in fuel flow in order to maintain the desired fuel utilization. The overall result should lower the oxidizer temperature to a value below its setpoint, which can be followed by further adjustments to turbine speed to increase the oxidizer temperature back to the setpoint.

For the NFCRC model, a different control strategy is implemented. A proportional integral (PI) controller is used to control the fuel flow rate in order to maintain the catalytic oxidizer temperature. Controlling the catalytic oxidizer temperature by adjusting the amount of fuel that enters the catalytic oxidizer can be accomplished by adjusting the total fuel flow entering the MCFC stack. For the case of a drop in load demand in the power plant, lowering the fuel flow rate will increase the fuel utilization in the MCFC stack and in turn lower the amount of fuel entering the catalytic oxidizer. In order to maintain fairly constant power from the gas turbine, the temperature of the catalytic oxidizer should remain approximately constant, and this can be achieved with such a control strategy. This should in turn maintain fairly constant mass flow through the gas turbine while the fuel utilization in the fuel cell is left to float. This control strategy may alter the MCFC performance, but it allows control of the catalytic oxidizer temperature and gas turbine performance parameters.

The goal of both of these control strategies is to maintain an adequate cathode flow and inlet temperature, a net power production from the gas turbine, while maintaining MCFC temperature near an optimal operating temperature. It is generally accepted that the operating temperature of a MCFC is 650 °C. There is a balance between the MCFC performance and cell stack and component degradation that makes this a desirable temperature. A study done by Au [12] shows that if the operating temperature of the MCFC changes from 600 to 700 °C then the overall CHP power plant efficiency is not much affected.

Hybrid Dynamic "Closed Loop" Response

The predicted dynamic response to a drop in power demand of the two hybrid MCFC/GT system models, each with a control loop applied as described above to maintain catalytic oxidizer temperature, is presented in this section.

Figures 6-8 show the response of the MCFC/GT power plant to a drop in load demand with the fuel flow rate into the MCFC controlled to maintain the catalytic oxidizer at a reference temperature. Figure 6 shows the initial drop in current produced by the MCFC stack due to the change in operating voltage. Given the voltage increase, the fuel utilization decreases due to the lower current. Each of the models predicts these overall impacts.

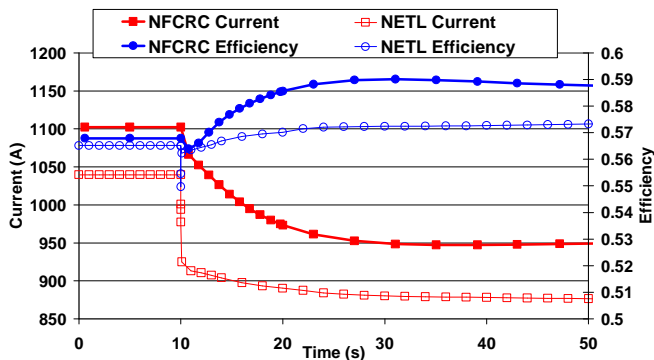


Figure 6. 1.08 m² Fuel cell response and overall hybrid efficiency during an increase of fuel cell voltage 0.76V → 0.77V for a closed system

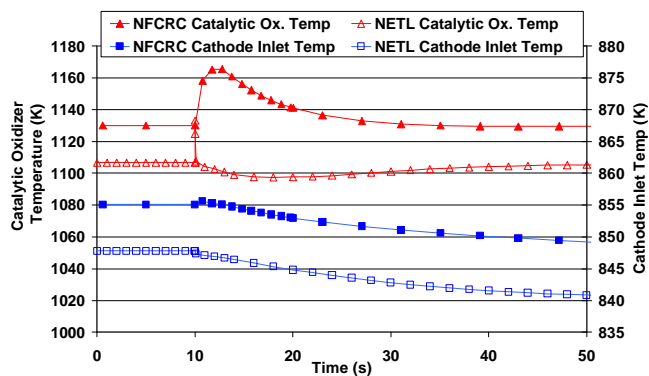


Figure 7. Catalytic oxidizer and cathode inlet temperature response during an increase of fuel cell voltage 0.76V → 0.77V for a closed system

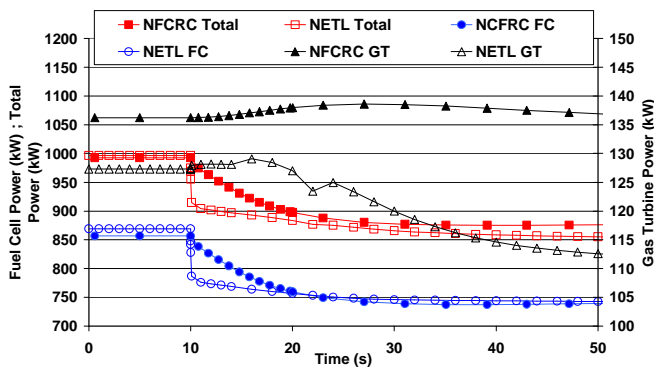


Figure 8. Power of fuel cell and gas turbine during an increase of fuel cell voltage 0.76V → 0.77V for a closed system

In order to maintain constant fuel utilization, the NETL model initially reduces the fuel flow in response to the perturbation. Because the fuel valve stroke time that is used is very small (1 ms) there is an almost immediate reduction in the fuel flow from the proportional action of the PID controller on the fuel valve. Thus the catalytic oxidizer temperature presented in Figure 7 also shows a sharp

reduction after the initial sharp increase, and this temperature is coincidentally approximately the original oxidizer temperature. After this the fuel controller continues to reduce the fuel flow in order to bring the fuel utilization back to its original value and this is why the oxidizer temperature continues to decrease. However, the turbine speed control begins to act by reducing the turbine speed to reduce airflow until the catalytic oxidizer temperature is back to its set point. Note that the NETL cathode inlet temperature does decrease slightly and so the oxidizer temperature set point would have to be increased to reach the original setpoint for cathode inlet temperature.

The NFCRC model, which incorporated a simple PI controller for overall fuel flow, based on the difference between the catalytic oxidizer temperature and its setpoint exhibits a different dynamic response. Each of the two control strategies requires approximately 35 seconds to bring the catalytic oxidizer temperature back to its setpoint. However, the simple control strategy used in the NFCRC model allows the catalytic oxidizer temperature to rise more than 30 degrees and linger at higher temperatures for a longer period of time than the NETL control strategy. The NFCRC controller parameters lead to an over-damped catalytic oxidizer temperature response, suggesting that modifications to the proportional and integral gains on the controller could improve the dynamic response.

The results of Figure 6 show that the predicted fuel cell current and overall hybrid efficiency of the two hybrid system models are different before the perturbation as discussed earlier. The MCFC stack currents do approach the same values, but the NFCRC MCFC approaches this state more slowly due to the slower fuel flow rate controlled response. The gas turbine power for each model presented in Figure 8, reflects the differences in the two control strategies. The NETL gas turbine power decreases due to the drop in load on the generator allowing the shaft speed to increase and the air flow rate to increase. NFCRC gas turbine power shows a small temporary increase due to the increase of the catalytic oxidizer temperature and TIT. This increase in gas turbine power and the decrease in fuel flow rate allows the NFCRC hybrid system to reach higher efficiencies as seen in Figure 6.

Even though the control strategy for the NFCRC MCFC/GT hybrid system leads to a more efficient operating condition, the corresponding sharp rise in catalytic oxidizer temperature for any length of time may not be acceptable. This temperature could melt the catalyst. One may desire the quicker response that the NETL model provides over a more efficient strategy in order to extend the life of this system. At the same time, if the masses of the heat exchangers are much larger, then the controller response time may be sufficient.

As mentioned earlier, the heat exchangers that are modeled in each hybrid system are different. When combined with the different control strategies that are applied, the heat exchangers create the observed predicted performance differences of the two hybrid system models.

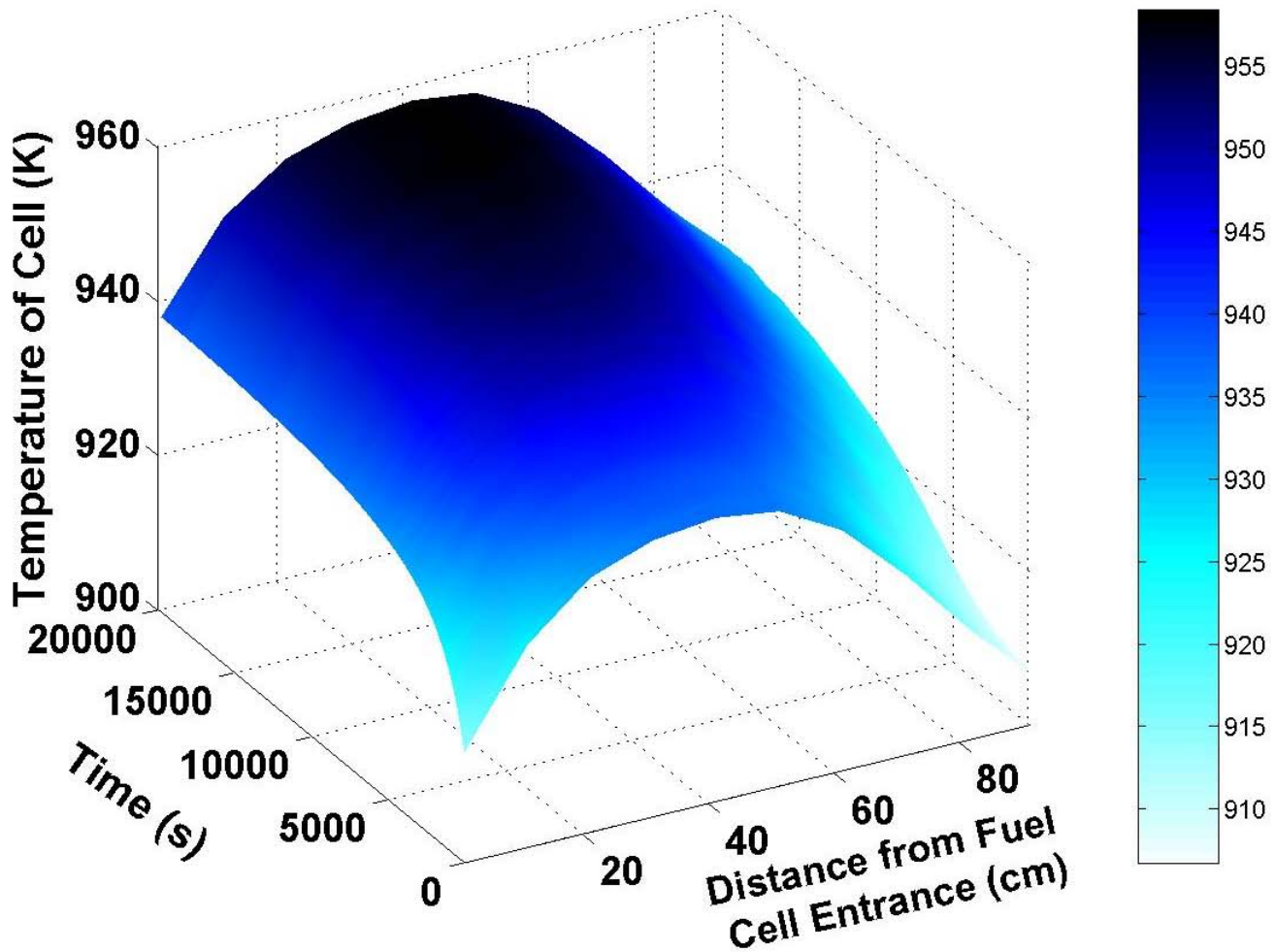


Figure 9. Temperature profile in the MCFC during the open loop voltage perturbation

Rise in Cathode Inlet Temperature

As pointed out earlier, maintaining proper temperature control with the various components and gas streams throughout the hybrid system is very important. One critical temperature that was focused on was the cathode inlet temperature. Controlling this temperature is very important in operating the MCFC stack at a safe and desirable temperature. For the open loop dynamic response for the MCFC/GT hybrid system it was shown in Figure 4 that if the MCFC stack experiences a 0.01 V change or a 5% change in power demand that the cathode inlet temperature can rise 30° C. Figure 9 presents the temperature profile in the MCFC as a function of time and distance from the entrance of the fuel cell gas streams. Figure 9 shows that the entire MCFC temperature profile rises around 30° C as well. This results in peak internal temperatures that approach dangerous levels of 955 K (682° C). This high temperature is extreme enough to degrade the performance and the life of the MCFC. And this result arises from only a small perturbation in power demand on the system.

SUMMARY AND CONCLUSIONS

The comparison of two different MCFC/GT models developed and applied in two different simulation environments resulted in good agreement. The models were able to predict the same trends and responses and significantly showed similar time scales associated with the dynamic response of hybrid fuel cell gas turbine system components and operating conditions. Steady state predictions of MCFC performance demonstrated similar predictive capabilities for the two fuel cell models. A MCFC/GT cycle of the type designed by FuelCell Energy, Inc. was presented and simulated. The simulated open-loop uncontrolled dynamic response of this MCFC/GT system to a fuel cell load perturbation was presented. The dynamic responses of the two hybrid system models compare well. Closed-loop dynamic responses of the hybrid system to fuel cell load perturbations using two different control strategies are also presented.

Several differences between the two hybrid system models are noted, due in large part to the differences in the specific heat exchanger and gas turbine models used. The gas

turbine models used different compressor and turbine maps and were set at slightly different design conditions, while entirely different heat exchanger technology was assumed in the respective models. The results point to important precautions for both modeling and designing an MCFC/GT system. The performance of subcomponents such as heat exchangers and control algorithms can dictate success or failure for these systems. The correct heat exchanger for the application can determine whether or not a system will properly operate.

The results suggest that control strategies that are implemented in hybrid MCFC/GT systems need to be robust yet flexible enough to allow the system operate under various conditions. The simple control strategies implemented in this paper were capable of controlling the hybrid system during a simple fuel cell load perturbation. In the case of more complex perturbations or operating conditions, such as those extant with being connected to the grid, more sophisticated control schemes should be considered. Nonetheless, the current model dynamic predictions suggest that control of these complex hybrid systems is quite feasible.

Hybrid fuel cell systems must be designed to be able to recover and maintain safe and efficient performance at all times. The models developed and applied in the current paper can be valuable tools applied to study a large number of complex perturbations and control strategies to gain confidence that the hybrid system (components + controls) that one desires will function properly.

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