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Experimental and theoretical evidence for control requirements in solid oxide fuel cell gas turbine hybrid systems

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ABSTRACT

Hybrid fuel cell gas turbine sensitivity to ambient perturbations is analyzed using experimental and dynamic simulation results. Experimental data gathered from the world's first pressurized hybrid SOFC–GT system tested at the University of California, Irvine, capture performance variations due to diurnal temperature oscillations. A dynamic modeling methodology demonstrates accuracy, robustness, and clearly identifies critical system sensitivities that require additional control systems development. Simulation results compare favorably with dynamic experimental responses. Predictions of component temperatures, pressures, voltage and system power exhibited 5 °C, 2 kPa, 2 mV, and 0.5% error respectively. Moderate ambient temperature fluctuations, 15 °C, caused variations in stack temperature of 30 °C, and system power of 5 kW. Small to moderate changes in fuel composition produced 30 °C shifts in stack temperature and 25% changes in system power. Simple control loops manipulating fuel cell air flow through SOFC bypass and inlet temperature through recuperator bypass are shown to effectively mitigate internal temperature transients at the expense of reduced system output. The observed temperature fluctuations resulting from typical environmental perturbations are of concern for performance loss and diminished longevity. Experiments and dynamic simulation results indicate the importance of integrated control systems development for hybrid fuel cell gas turbine systems.

1. Introduction

New challenges arise from increasing environmental and political concerns regarding natural resources and environmental protection. These societal issues, coupled with the ever growing demands of an energy intensive lifestyle, highlight the insufficiencies of current power generation technologies. Hybrid solid oxide fuel cell/gas turbine (SOFC/GT) technology is a continuous generation technology that offers the possibility of higher efficiency combined with lower emissions [1–4]. Commercialization of advanced hybrid SOFC/GT technology requires considerable improvement of core component (e.g., pressurized SOFC) performance, system integration, and dynamical control [5–7]. Mathematical modeling provides cost-effective understanding that combined with demonstration and verification experiments can aid in the continuing development of SOFC/GT technology and control strategy testing [8–10].

Solid oxide fuel cells (SOFC) employ a range of material sets and designs that operate between 800 and 1000 °C [10]. The high operating temperatures, combined with the ceramic fuel cell ability to operate at elevated pressure, raise the possibility for thermal integration with additional devices and end-uses. Combined heat and power applications [11–13] or integration with a gas turbine generator [14–17] are two promising SOFC system design options. In the SOFC/GT hybrid system, the fuel cell high temperature SOFC exhaust drives a gas turbine, providing air flow and pressurizing the SOFC while driving an electric generator that produces additional electrical power. As a result, SOFC/GT hybrid systems have demonstrated efficiencies above 50% [5,18] and studies have shown the possibility for electrical conversion above 70% [4,19] when operating on natural gas and above 60% in an integrated coal gasification plant [6,19]. Higher efficiency reduces CO_2 emissions while separated fuel and air flows in the SOFC allow system designs for CO_2 sequestration with minimal performance cost [16,20,21]. Nitrogen oxide emissions are nearly eliminated since the SOFC/GT primarily employs electrochemistry rather than combustion. High efficiency and low emissions make hybrid SOFC/GT technology an attractive option for meeting future power demands.

In the U.S., the Solid-State Energy Conversion Alliance (SECA) directed by Department of Energy (DOE) is currently developing innovative, high performance, low-cost SOFC technology [5]. Similar SOFC technology development programs have been rapidly advancing SOFC technology in Europe and Japan [22,23]. At the system design level both prototypes and mathematical modeling

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have developed multiple system designs and control strategies [8,19,24–27]. The current work seeks to illustrate the fidelity of the hybrid system modeling methodology developed at the National Fuel Cell Research Center [10,18,24,28,29] and draw attention to critical system sensitivities caused by fluctuations in temperature, electrochemical current, and fuel composition variations.

2. Background

Successful numerical models of hybrid systems must balance accuracy and computational efficiency to capture the physical transients occurring at the electrochemical, mechanical, and bulk thermal time scales. Like all hybrid devices the interesting dynamic interactions in SOFC/GT systems occur due to the interconnected and highly coupled nature of the different components as they that interact and respond to each other during operation. These interactions can be complex, depending both upon the dynamic response characteristics of each component and the coupled responses of the integrated system. Feedback can cause small perturbations in one system, for instance the turbo-machinery, to exacerbate fluctuations in a connected system, a pressurized fuel cell. Some feedback can be beneficial and improve stability; other feedback requires constant control action to maintain operating limits. Because of these complexities, significant previous and ongoing research has developed and applied dynamic modeling to SOFC/GT technology to analyze system behavior, transient performance, and load following capability [2,5,6,8,9,22,25,26].

Lukas et al. developed a dynamic model of a molten carbonate fuel cell (MCFC) stack [30] based on principles of energy and mass conservation and several simplifying assumptions. The authors matched transient performance data from a demonstration MCFC plant, and concluded that the dynamic model sufficiently captured the physical response to further investigate transient behavior and control strategies [31].

Mueller et al. developed a dynamic model of a Siemens Westinghouse 25 kW tubular SOFC system [32]. The resulting tubular SOFC stack model was sufficiently robust to allow integration with additional modules for other system components (e.g. reformer, combustion chamber, and dissipater). The model used a quasi-two-dimensional approach for simulating major components by discretizing each component in the primary flow direction and resolving important physical and chemical processes in the cross-wise direction. A steady-state comparison suggested that the integrated model could predict measured system power performance to within 3%, and temperature to within 5%. The characteristic transients of the system including voltage, temperature, and performance, reflected those of a representative tubular SOFC system. Mueller et al. also developed a dynamic 60 kW gas turbine model [33] with transient load following controls. It was later applied to an integrated system forming an SOFC/GT hybrid system. The transient response of the hybrid outperformed that of the gas turbine and independently operated SOFC. The SOFC/GT hybrid demonstrated excellent transient load response while remaining well within critical operating limits.

Additional work, conducted by Stiller et al., developed a dynamic SOFC/GT hybrid model that was also spatially discretized and used it to conduct steady-state and dynamic studies on hybrid systems [34]. The SOFC model captured the dynamics of gas transport and heat transfer. The compressor and turbine models were based upon performance maps of a small centrifugal compressor and radial turbine, respectively. The work focused on the operating envelope and safety margin for various control strategies.

Kaneko et al. also developed a dynamic SOFC/GT hybrid system model [18]. They studied the performance characteristics of the SOFC/GT hybrid system operating on biomass gas with fluctuating species concentrations, and developed a power and temperature control strategy to cope with such transients. Ferrari et al. focused the efforts of a dynamic SOFC/GT hybrid system model on determination of the three primary time scales; the fluid dynamic time-scale (less than 1 s), the pressurization/depressurization characteristic time-scale (about 100 s), and the heat exchanger thermal inertia time-scale (over 300 s). A fuel ejector model simulated recirculation and mixing of anode off-gas with fresh fuel. Ejector performance significantly affects the fuel steam-to-carbon ratio, which in-turn affects reforming reactions and carbon formation in the reformer and stack.

Mueller et al. studied transient load following capabilities of SOFC/GT hybrid systems [35] and determined that anode compartment fuel depletion limited transient load-following capability [36]. The authors proposed a new control strategy and several design considerations to compensate for fuel lag and maintain operating conditions throughout transient operation. Campanari et al. developed a tubular SOFC model discretized into 100 segments [37] and verified simulations against an atmospheric and pressurized SOFC system. The authors concluded that a Nusselt number approximation of four is valid and that diffusion losses are negligible at the high SOFC operating temperatures.

Gariglio et al. presented experimental data of two operating SOFC prototypes in Torino, Italy [38]. The CHP100 produced 100 kW electrical and 60 kW thermal. The SFC5 Alpha6 produced 3.5 kW of electrical and 3 kW of thermal power. Fuel utilization was varied from 78 to 81% and stack temperature from 960 to 973 °C. Both prototypes demonstrated similar voltage responses to fuel utilization changes, despite the vast difference in size, but different responses were observed for changes in operating temperature.

The scope of previous research indicates that several groups have focused research upon the dynamics of fuel cell or fuel cell/GT hybrid system simulations, but few studies have compared dynamic simulation results with experimental data. The first attempt at dynamic SOFC/GT simulation by Roberts and Brouwer detailed a pressurized 220 kW SOFC/GT hybrid system. The simulation compared favorably with data from transient operation [10]. The model captured the dynamic performance of both the gas turbine and SOFC stack during transient start-up conditions. The current work builds upon this effort by extending the dynamic model to simulate different operating conditions and evaluating the predicted performance against experimental observations for a diurnal ambient temperature variation. Additionally, critical system sensitivities to ambient temperature, electrochemical current, and inlet fuel composition variations are evaluated.

3. System design

The system studied was the world's first pressurized SOFC/GT hybrid system; developed by Siemens Westinghouse and tested at the NFCRC with support from Southern California Edison, the California Energy Commission, the U.S. Department of Energy, and others. The effort undertaken utilizes valuable experimental data from this initial technology demonstrator. The project objectives were threefold; design and integrate high quality components into a hybrid system, demonstrating that an integrated system can be operated within design parameters, and provide operational information and experience on performance characteristics. Each objective was met with resounding success [39] as the system achieved 53% fuel-to-electricity conversion efficiency while operating over 2900 h.

The natural gas fueled 220 kW SOFC/GT hybrid system is shown in Fig. 1. An SOFC stack, direct and indirect internal reformers, two combustors, two gas turbines, a compressor, multiple heat exchangers, and an AC generator comprise the advanced hybrid

Fig. 1. Pressurized 220 kW SOFC/GT hybrid system.

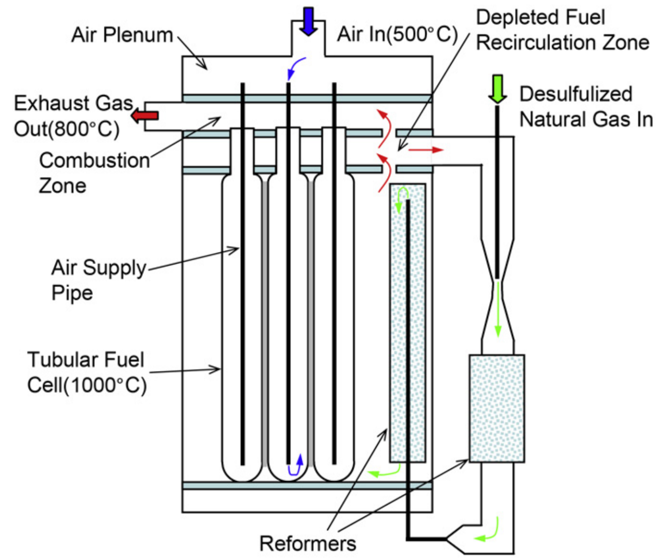

Fig. 3. Representation of the tubular SOFC stack.

demonstrator. Vertically mounted tubular cells, 1152 of them, comprise the SOFC stack (Fig. 2). The stack comprises 3 parallel strings of 384 series connected cells operating near 1000 °C. As shown in Fig. 3, a fraction of depleted anode gas recirculates to reformer panels (installed between individual rows of tubular fuel cells) providing heat and steam for natural gas reformation. The remaining gas flows into the combustion zone, mixes with depleted air, and burns. The pressurized stack operates at 3 atmospheres enabling the nominal 100 kW SOFC stack to produce 180 kW. The two-shaft gas turbine system comprises a compressor, high-pressure turbine, low-pressure turbine and AC generator. The 60 kWe-rated gas turbine produces considerably less power in the hybrid system due to the relatively low turbine inlet temperature compared to stand-alone operation. The two combustors are used only during system startup and shutdown.

The 220 kW SOFC/GT hybrid system dynamic model is developed in Matlab/Simulink® following upon the work of Roberts and Brouwer [10] using the modeling methodology developed at the National Fuel Cell Research Center [28,29]. The model is comprised of an SOFC stack with internal reformer, compressor, gas turbines, combustors, and heat exchangers. The appropriate heat transfer, pressure drop, chemical, and electro-chemical reactions are chosen for each of the components and overall system based upon the assumptions listed below. Dynamic equations of mass, momentum, and energy conservation are solved in each of the component models. Refer to Mueller et al. [40] and McLarty et al. [28,29] for a description of the governing physics underlying each system component of the dynamic model.

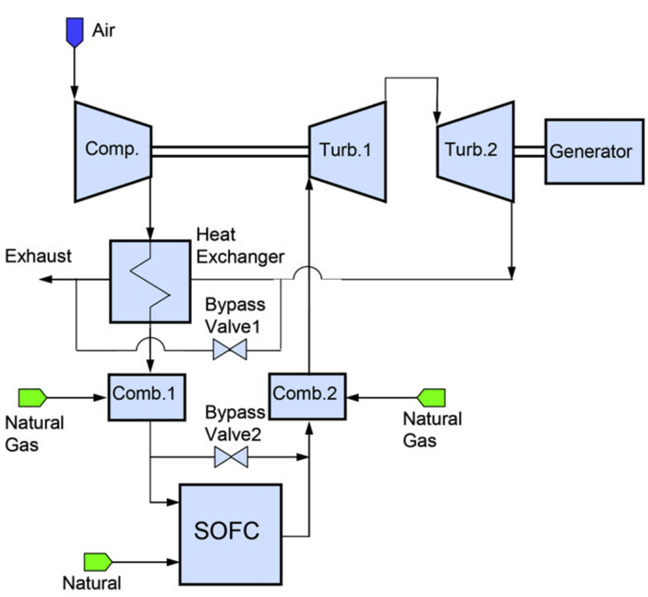

Fig. 2. Schematic of the pressurized 220 kW SOFC/GT hybrid system.

3.1. Assumptions

1. Uniform temperature, pressure, and species mole fraction distributions within each control volume.
2. Ideal gases throughout.
3. Two dimensional (flat plate) reformer and heat exchanger models.
4. Well-developed laminar flow internal to the fuel cell.
5. Gas is treated as a compressible fluid throughout all components other than the fuel cell.
6. Species other than the following do not significantly affect system performance: methane, carbon monoxide, carbon dioxide, hydrogen, water, nitrogen, and oxygen.
7. Hydrogen is the only electrochemically active species (Carbon monoxide does not directly participate in electrochemistry, but reacts through water-gas shift reaction).

3.2. SOFC model

Table 1 shows the tubular SOFC model parameters, which were determined by fine-tuning of the parameters of Roberts and Brouwer [10] to match the steady-state conditions at the beginning of the nearly 60 h fixed operation period presented in the results.

Table 1
SOFC model parameters.

Parameter	Value	Unit	Description
N_{cell}	1152	–	Number of cells
D_A	0.0223	m	Cell outside diameter
D_C	0.0176	m	Cell inside diameter
OD_{asp}	0.0148	m	Air supply pipe outside diameter
ID_{asp}	0.0088	m	Air supply pipe inner diameter
L	1.5	m	Cell length
ρ_{asp}	3970	kg m^{-3}	Air supply pipe density
ρ_e	1500	kg m^{-3}	Electrolyte solid density

Note that the SOFC stack used in the current study was modified from that used in the experiments of Roberts and Brouwer. The spatially discretized fuel cell captures variations in fuel and oxidant concentrations allowing for accurate local predictions of current density and voltage. The modified inlet geometry captures the internal transfer of heat from the stack to inlet air through radiative heating and convection. This methodology was shown to be highly predictive of stack performance and transient behavior dynamics for several comparisons to experimental data [28,29].

3.3. Compressor and gas turbine model

The turbo-machinery models utilize generic performance maps acquired from GasTurb® and fundamental equations for isentropic compression and expansion modified by an efficiency factor determined from performance maps. Two non-dimensionalized maps are scaled and interpolated for mass flow and efficiency as a function of normalized pressure ratio and rotational speed for both the compressor and turbine. The maps are comprised of empirical data from a generic radial compressor and gas turbine then scaled to match the steady-state performance of the Ingersoll unit. The efficiency map of the turbine required modification to match the response of the system once integrated with the FC, with the trend toward higher isentropic efficiency at higher normalized shaft speed reversed to a trend of decreasing isentropic efficiency. A dynamic pressure equation balances the turbine outlet pressure, turbine inlet flow rate and the flow rate determined from the performance maps to find the turbine inlet pressure and thus compressor outlet temperature. This same approach has been employed in previous studies, resulting in accurate simulation of experimental data [32,34]. The shaft speed of the power turbine (GT2) is fixed because it is connected to an AC generator. Meanwhile the shaft speed dynamics of the compressor-connected turbine (GT1) are solved by the dynamic torque balance expression.

3.4. Heat exchanger and combustor model

Heat is re-circulated within the cycle through a heat exchanger transferring energy from the post- fuel cell turbine exhaust to the pre-fuel cell compressor discharge. A nodal model simulates the heat transfer via convection and conduction in a flat plate counter flow heat exchanger. The discretized heat exchanger model is able to capture the relatively large temperature gradient in the stream wise direction and accurately model the correct heat transfer rates.

The bulk combustor model assumes complete combustion and employs conservation of mass and energy equations to determine molar fractions and combustor exit temperature. The temperature and species concentration dependence of heat capacity is solved by an iterative solution during the calculation of combustor exit temperature when a significant rise in gas temperature occurs.

4. Experimental results and model comparison

4.1. Experimental conditions and results

An operating electric generator can be subjected to a multitude of perturbations of differing magnitude and importance. This study aims to isolate a single perturbation, ambient temperature, in order to determine the relative effects on system performance and identify any need for additional compensating controls. The first operational test of a FC–GT hybrid at the NFCRC yielded valuable data even while operating under "fixed" conditions.

Fig. 4 displays the observed and simulated diurnal temperature variations at the compressor inlet and the measured inlet fuel flow

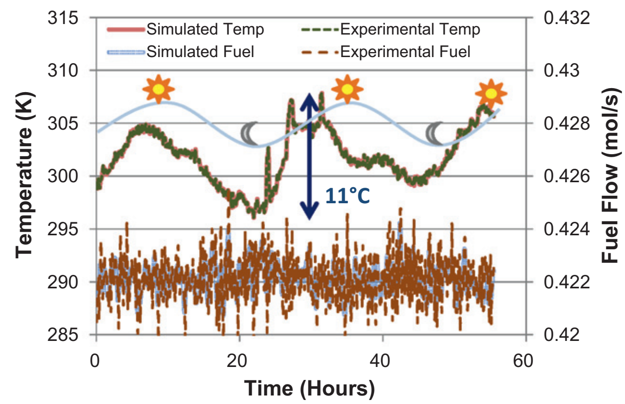

Fig. 4. Compressor inlet temperature (left axis) and fuel flow observed and simulated (right axis).

which varies less than .5%. For the experiments of interest the system was operated at fixed fuel flow and bypass for a period of 60 h. The effects of ambient temperature can be viewed during two diurnal cycles in which the ambient air temperature fluctuated from daily minimums of 23 °C occurring around 5 AM to daily maximums of 33 °C occurring at 2 PM. The diurnal temperature cycle is the perturbation of interest and will be signified on each chart to highlight a reinforcing or damping impact. The fixed operating conditions and ambient fluctuations were simulated using the NFCRC developed dynamic physical model yielding results that well corresponded to the experimental measurements. Three temperature spikes correspond to maintenance and inspections opening the cabinet housing containing a heating air duct for the compressor inlet air flow.

The first observation is that the system output increases with rising ambient temperature and decreases with falling ambient temperature, Fig. 5. This trend is most pronounced in the SOFC system which varies in output by as much as 5 kW and is opposite typical expectations for a generator. Indeed, the more typical gas turbine output exhibits the opposite trend and reduces the overall system perturbation. Looking further we will find that uncontrolled shifting of power generation from one device to the other will have a pronounced impact on the operating state of both generators. The higher inlet temperature and reduced air density are expected to raise the internal temperature of the SOFC stack. The unexpected shaft speed response further reinforced this impact by providing significantly less air flow at reduced speed during the warmer periods when cooling air was most critical, as shown in Fig. 6. The speed response of the turbine

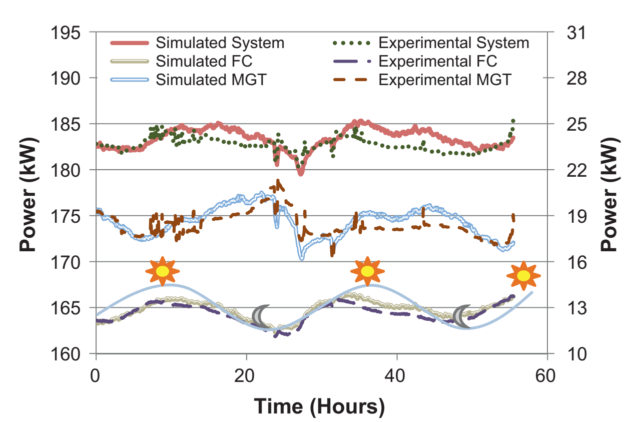

Fig. 5. Observed and simulated system, fuel cell stack, and MTG (right axis) power output.

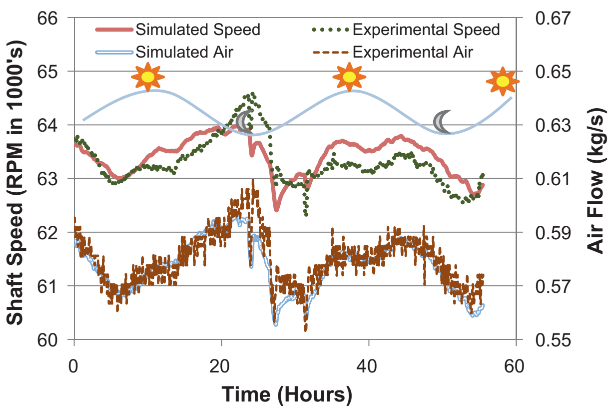

Fig. 6. Observed and simulated shaft speed (left axis) and air flow rate (right axis).

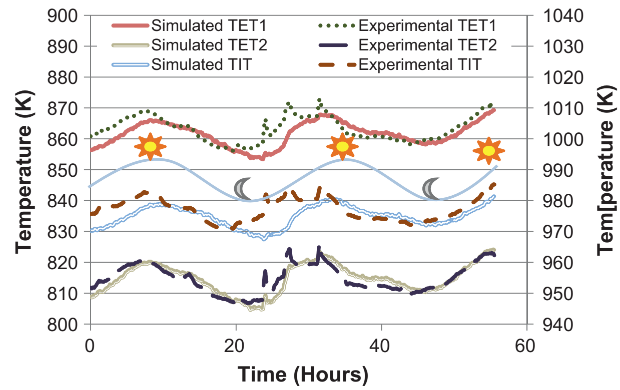

Fig. 8. Observed and simulated turbine inlet (right axis), GT1 exhaust (left axis) and GT2 exhaust (left axis) temperatures.

was unexpected as typically the hardware responds to increasing inlet temperatures with increased speed operation. The data suggests that turbine inlet temperature response, Fig. 7, is in phase and corresponding to the ambient temperature as would be expected for a MTG without FC. Therefore the speed response, an inverse relationship with turbine inlet temperature, is completely unexpected and is likely a result of significant deviation from typical operating conditions. This response is troublesome as it can lead to sudden over-speeding during emergency shutdown procedures if sufficient thermal energy is not provided at the turbine inlet.

This hybrid system derives the bulk of its electrical output from the fuel cell, which is strongly influenced by the operating temperature. With increased compressor inlet temperatures the flow rate can be seen to decrease due to both the reduced air density and shaft speed, as shown in Fig. 6. The reduced air flow rate from the compressor insufficiently cools the fuel cell to the desired operating temperature of 925 °C and instead results in an operating temperature above 950 °C, as shown in Fig. 7. It is important to recognize that the temperature fluctuation experienced by the fuel cell is more than triple that observed at the compressor inlet. This “amplification” of ambient perturbations poses a potentially harmful system response and significant threat to the durability and lifetime of the fuel cell. The cause of the amplification is the coupled impact of inlet temperature and air flow rate. The air flow rate change is greater than expected due to the unexpected shaft speed response discussed previously. The characteristic decrease in Ohmic polarization at higher operating temperature slightly damps the impact of ambient temperature variation, and thus minimizes the impact on most stand-alone fuel cells. However, the coupled response of the reduced air flow driven by the attached turbo-machinery of the hybrid SOFC–GT system overcomes this natural damping and exacerbates the ambient fluctuation.

Measured air flow rate decreases by as much as 10% during the warmer daytime hours and cannot be easily controlled with the existing dual-shaft turbo-machinery. The only means for modification of the fuel cell inlet flow rate was the fuel cell bypass valve. Under nominal and experimental conditions the valve remained 3% open. Control simulations employing bypass control quickly saturate, and cannot recoup the 10% loss of air flow provided by the compressor.

4.2. Model comparison

Figs. 5–10 demonstrate the accuracy of the turbo-machinery modeling. Pressures, temperatures, and flow rates are predicted with good accuracy at multiple points throughout the system. Measured turbo-machinery inlet temperature, outlet temperature and flow rate are predicted to within 1%, 1.5% and 2% error, respectively (Figs. 8 and 10). The spatially resolved dynamic model matches measured parameters of SOFC temperature, voltage and power, which are simulated to within 4 °C, 2 mV and 0.2% error respectively. The presented SOFC temperature, a numerical average of 15 distinct local measurements, corresponds well with the magnitude of the simulated response. The 15 thermocouples were placed on 5 tubular cells at the top, middle, and bottom. A tube near the center and 4 periphery tubes

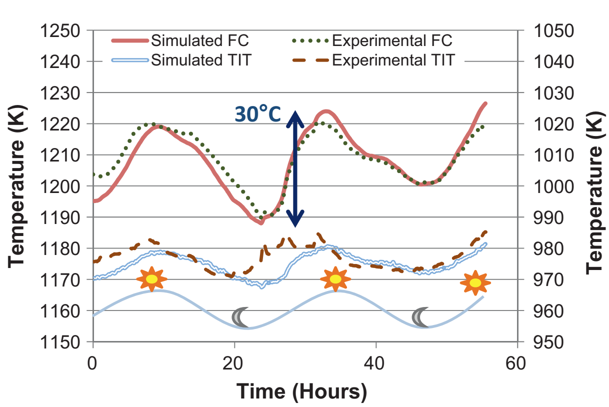

Fig. 7. Observed and simulated fuel cell (left axis) and turbine inlet (right axis) temperature.

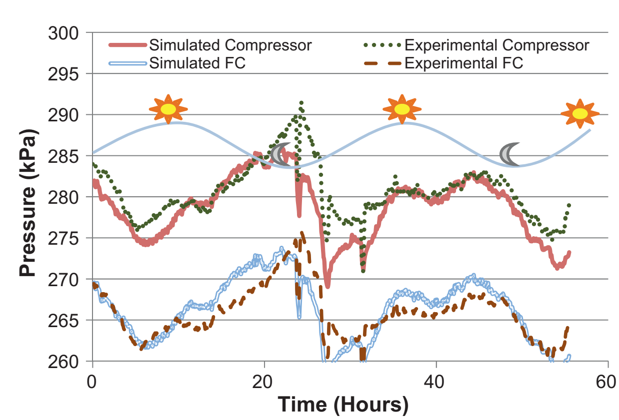

Fig. 9. Observed and simulated compressor and FC exit pressures.

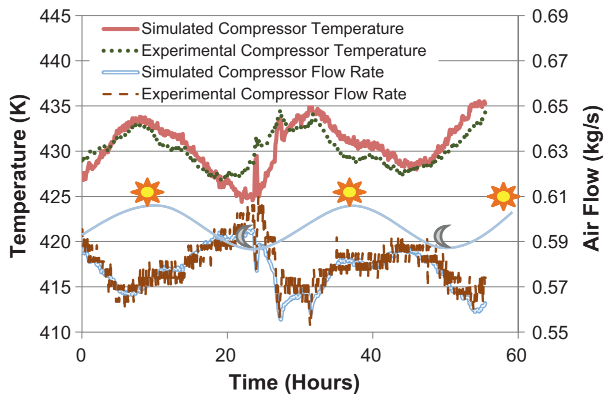

Fig. 10. Observed and simulated compressor flow rate (right axis) and temperature (left axis).

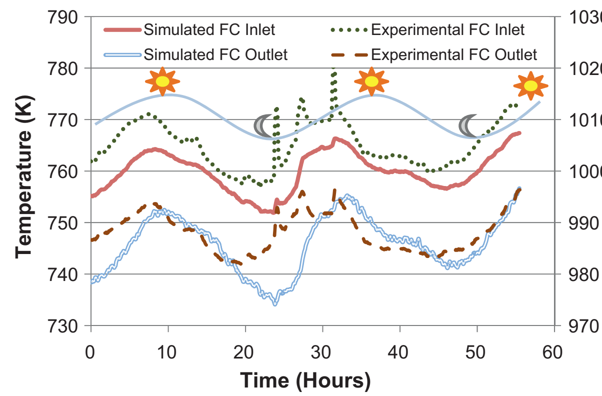

Fig. 11. Observed and simulated fuel cell inlet (left axis) and outlet (right axis) temperature.

were chosen to identify internal thermal distributions. It was found, as expected, that the length of the tube experienced the most significant temperature distribution, whereas the different tubes experienced only slightly different temperature profiles with the corners being slightly cooler than the center. The spatial distribution of thermocouples could account for some of the discrepancy in the lag time between ambient temperature changes and fuel cell temperature changes that is observed as the simulation utilizes boundary conditions that mimic the center tube of the bundles. Some measurement locations varied significantly more than others suggesting a local dependence of the perturbation upon SOFC operating temperature that may be caused by reformation kinetics or changing gas flow distributions. Large local variations pose a challenge to stack power management (exceedingly low temperature in certain locations) and degradation (exceedingly high temperature in certain locations). Detailed measurements of internal temperature variations and species concentrations were unavailable, but a detailed reformation and electrochemical model is employed in the model and sufficiently models the interaction with flow rate and inlet temperature measured in the experiment. By accurately tuning the model to known physical dimensions and closely approximating transfer coefficients the linear spatial model resolution can offer additional insights of internal dynamics unavailable in the experimental data, such as the extent of internal reformation, local current densities, fuel distributions, and local temperature gradient fluctuations. These localized characteristics can affect the thermo-mechanical stress and degradation of the tubular fuel cell.

Examination of the difference between experimental data and simulated results shows a larger deviation occurs in components downstream of the FC and first stage turbine. The cause of the downstream imprecision can be expressed as a sum of multiple smaller upstream perturbations.

Looking closely at the sudden transients occurring due to heat exchange during the inspections (opening of cabinet doors) the simulation responds on a similar time scale and magnitude for the flow rate and pressure responses. The temperature response of the FC also exhibits a close correlation to data during these sudden transient instances; however the impact downstream of the fuel cell is less noticeable than observed in the experiment. The simulation predicts a slight damping of the transient behavior at the turbine inlet and outlet, but over predicts the magnitude of the fluctuation caused by the diurnal inlet temperature perturbation. It is possible that opening the cabinet caused additional heat losses at points other than the compressor inlet having a more direct impact on downstream components (e.g., air pre-heater) that the model was unable to capture (Fig. 11).

5. Sensitivity analysis and dynamic control

5.1. Magnified system response to ambient temperature

Experimental results from the pressurized fuel cell gas turbine hybrid system demonstrated a strong correlation between stack temperature and diurnal temperature fluctuations. The pleasant southern California weather offers relatively small daily and seasonal temperature fluctuations. Alternative locations may present more extreme climate and weather variations that could test the limits of this particular hybrid configuration without appropriate dynamic controls. The current dynamic physical model was constructed to simulate more extreme ambient conditions. A hypothetical temperature profile (Fig. 12) was applied to demonstrate diurnal temperature swings of 15 °C, and 30 °C on a summer day averaging 27 °C before decreasing to a winter low of minus 18 °C. The most critical responses are that of the fuel cell operating temperature and the net system power. Fig. 12 presents the applied temperature perturbation and the associated uncontrolled system response. The results indicate that seasonal temperature variations are capable of causing turbine over-speed in the extreme case, Fig. 14. The response shows how the uncontrolled hybrid system magnifies the ambient temperature perturbation to produce larger oscillations of the FC temperature. The simulation indicates a maximum FC temperature of 1085 K, a temperature at which the FC stack would not likely remain self-sustaining.

To avoid negative system response characteristics it is imperative to control the air flow rate and inlet temperature by manipulation of SOFC bypass and recuperator bypass. Fig. 12 presents the system response with SOFC bypass only, recuperator

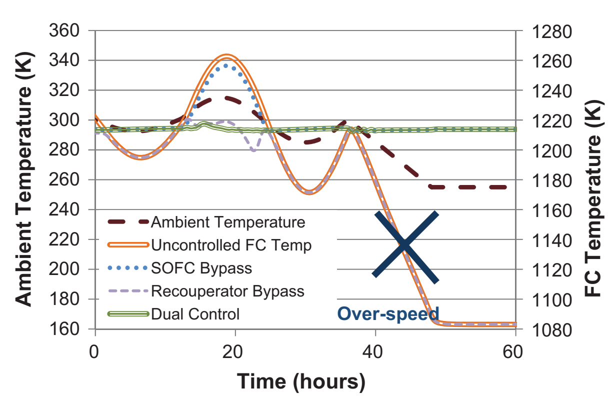

Fig. 12. FC temperature response to changing ambient temperature.

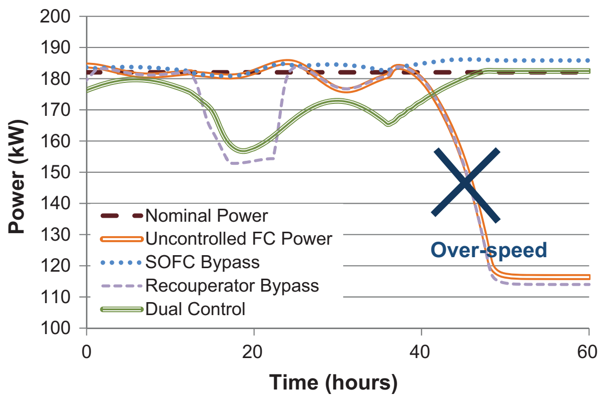

Fig. 13. System power response to changing ambient temperature.

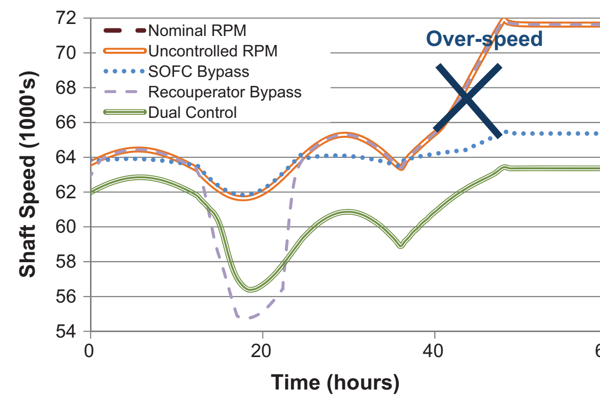

Fig. 14. Shaft speed response to changing ambient temperature.

bypass only, and both SOFC and recuperator bypass (dual control). SOFC bypass control does an excellent job when the stack is not producing enough heat and cooling air flow can be diverted away from the fuel cell, but fails to fully mitigate the high FC temperature excursions. Since the original bypass value is set at only 3% of nominal flow, SOFC bypass saturates rather quickly at 0% bypass when the ambient temperature rises. Similarly, recuperator bypass satisfactorily controls the FC temperature rises by diverting exhaust heat away from the system, but is unable to mitigate temperature drops due to control saturation. The combination of both controls (dual control) diminishes the impact of ambient temperature fluctuations, but causes severe diversions in system output, Fig. 13. Only SOFC bypass control compensates for the reduced cooling need, avoids turbine over-speeding and maintains an operable fuel cell temperature on cold winter days.

Fig. 13 presents the system output power with each of the above controls implemented. SOFC bypass control demonstrates minimal impact on system output, but recuperator bypass dramatically reduces the system power by 15% during the peak summer highs. As the stack temperature severely drops due to the simulated winter ambient temperatures the loss of fuel cell power causes a 30% decrease in net power. The combined response demonstrates robustness for minimizing temperature fluctuations, but at the cost of shifting and potentially magnifying the fluctuations in the power output. With both SOFC and recuperator control the power fluctuation is held to within 12% of nominal output while temperature and fuel cell output is maintained. The fluctuation in power is largely due to the changing output of the micro-turbine generator (MTG) when bypass flow cools the turbine inlet temperature. These dynamic responses foreshadow a distinct tradeoff in most hybrid fuel cell gas turbine control scenarios between system reliability and power output control. Fig. 14 presents the dynamic response of the turbo-machinery.

Operation of the system without controls resulted in a 300% FC temperature response to ambient temperature fluctuations. The dynamic simulation accurately captures this phenomenon, but demonstrates that simple control strategies can mitigate the temperature fluctuation of the fuel cell stack. This response is caused by the coupled impact of increased inlet temperature, lower compressor efficiency and decreased air flow that combine to raise the operating temperature of the fuel cell. The low turbine inlet temperature and increased pressure drop between compressor and turbine resulted in turbo-machinery operation well below design pressure and peak efficiency. Future SOFC/GT hybrid improvement can result from better turbo-machinery selection and advanced controls to compensate for perturbations such as the diurnal temperature perturbations investigated herein.

5.2. Fuel composition sensitivity

Natural gas composition varies significantly by region and season depending upon the original source location and demand. Small fluctuations in the amount of higher hydrocarbons, nitrogen, and sulfur can occur in real-time at any particular location. Natural gas suppliers often regulate the fuel Wobbe index to ensure a constant heating value to the end-user. A hypothetical fuel composition profile is applied to the current hybrid model to simulate a small compositional change that could occur at a typical installation, and a large compositional change that is less likely, but possible. These step change perturbations in fuel composition, shown in Figs. 15–17, occur at 12 and 36 h. The Wobbe index divides the higher heating value (HHV) by the root of specific gravity (SG) relative to air at 1 atm pressure. Two fuels with equal Wobbe indices would release nearly the same heat during combustion when driven through a fixed nozzle by a fixed pressure differential. The specific gravity term in the Wobbe formula partly captures the density variations that would result in a changing mass flow through an orifice as follows:

$$W_1 = \frac{\sum \mathrm{HHV}_i \times X_i}{\sqrt{\sum \mathrm{SG}_i \times X_i}} \tag{1}$$

Natural gas suppliers regulate the Wobbe index, because this generally provides a constant heating value for diffusion flame burners. Fuel composition is a larger factor in electrochemical generators such as fuel cells, and thus variations in methane from as much as 95% to as little as 75% affect a fuel cell hybrid system more significantly than a typical combustion device. A simulated switch between three natural gas fuels with identical Wobbe index values was analyzed using the current model. The initial fuel composition was 95% CH_4, 2.5% CO_2, and 2.5% N_2, the second fuel composition

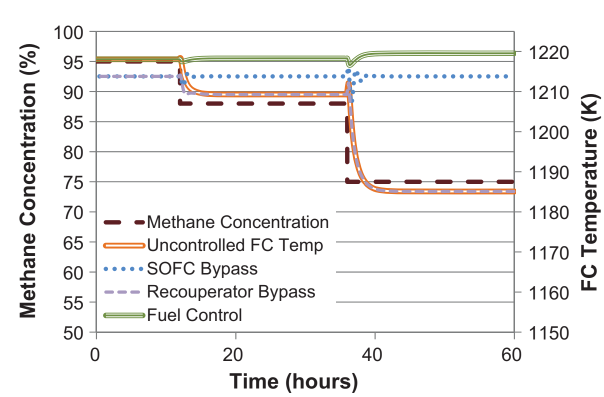

Fig. 15. FC temperature response to changing fuel methane content.

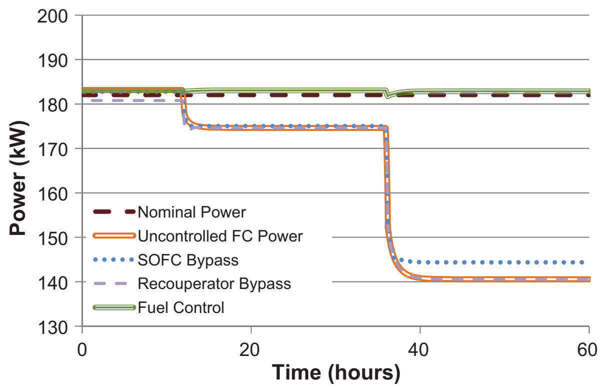

Fig. 16. System power response to changing fuel methane content.

was88% CH_4, 4.6% CO_2, 5.4% H_2 and 2% N_2 and the final fuel composition was 75% CH_4, 10.84% CO_2, and 14.16% H_2. The Wobbe index remained fixed at 1153 BTU ft^{-3}; which is typical for California natural gas supply

The combination of fuel composition and temperature perturbations that could be detrimental to performance suggests a need for careful monitoring and control of incoming gas composition. The simulation illustrates SOFC gas turbine hybrid system sensitivity to fuel composition variations that are likely to be experienced in the field. Once again the uncontrolled system is simulated and compared to the response with SOFC bypass and recuperator bypass. The third method of control investigated is fuel flow rate control instead of dual control. Fuel flow rate is manipulated to maintain fixed fuel utilization and was found to completely offset any changes in fuel heating value. Figs. 15–17 demonstrate that fuel composition changes can decrease SOFC temperature by as much as 30 °C and system power by 25%. SOFC bypass can effectively maintain SOFC temperature for the lower power outputs, but recuperator bypass is ineffective. Fuel flow control performs well as it can be implemented in a feed forward manner if the inlet composition is known. If unknown, a fuel cell voltage measurement may provide an index related to fuel composition that could be used in a similar manner for fuel flow rate control.

6. Summary and conclusions

A dynamic model of a 220 kW tubular SOFC/GT hybrid system was applied to simulate the transient operation of an experimental 220 kW hybrid SOFC/GT system that was subjected to a diurnal ambient temperature change perturbation. The simulation matched well with experimental observations. The model predicted voltage to within 2 mV, average component temperatures to within 5 °C, operating pressure to within 2 kPa, and overall system power to within 0.5%. The steady-state accuracy and similarity of dynamic response characteristics between model results and experimental data show that the current approach can reasonably simulate the transient performance characteristics of interest, namely, the response to diurnal temperature fluctuations. The approach uses simplified geometric resolution of the dynamic physics, chemistry, heat transfer and electrochemical equations integrated into a complex hybrid system dynamic model. The primary reason for the observed amplification of diurnal temperature changes in fuel cell stack temperature was the coupled effect of air density, compressor efficiency and air temperature in reducing air flow with increasing ambient temperature and vice versa.

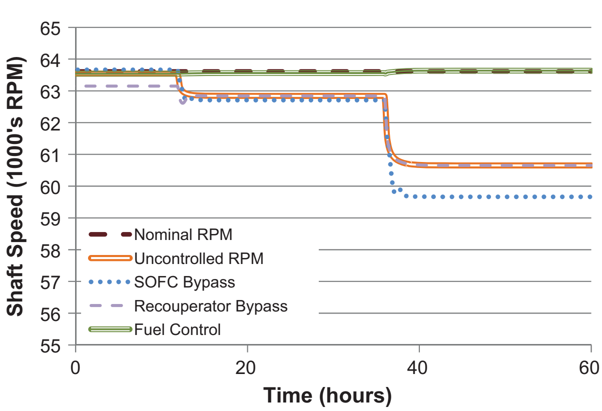

Fig. 17. Shaft speed response to changing fuel methane content.

Temperature control of the fuel cell is critical in mitigating degradation mechanisms and mechanical stress. Excessive temperature, thermal cycling, and large temperature gradients increase the risk of failure due to mechanical stress and increase the rate of degradation due to catalyst migration and carbon deposition. The impact of ambient temperature perturbations on stack temperature was shown through simulation to be mitigated by manipulation of air flow rate using SOFC bypass and fuel cell inlet temperature using recuperator bypass. This control strategy maintains a desirable average stack temperature but may still lead to local temperature gradients in excess of design specifications. Control of fuel utilization and current density may be necessary for cell longevity particularly for fuel cells with internal reformation. Since the SOFC operating temperature is important to cell operation, efficiency, and cell degradation, the impacts of ambient temperature changes should be considered in future hybrid system design.

Additional control systems development should be made to address potential variations in fuel composition, particularly in the application of bio-fuels or syngas. SOFC bypass control was shown to effectively compensate for fuels with reduced effective hydrogen content and recuperator bypass was shown to be ineffective. Feed-forward fuel control for maintaining fixed fuel utilization provided the best response to changing fuel compositions. Hybrid FC–GT systems with sufficient control measures, such as SOFC bypass, recuperator bypass, and fuel flow control, are shown to effectively minimize transient impacts on the fuel cell within the range of function of the gas turbine. Additional combustor firing and compressor bleed may extend the operability range of the gas turbine to produce a highly flexible and responsive hybrid system. Similar control strategies should be strongly considered as integral control aspects in future plant designs.

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