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CHARACTERIZATION OF AIR FLOW MANAGEMENT AND CONTROL IN A FUEL CELL TURBINE HYBRID POWER SYSTEM USING HARDWARE SIMULATION

David Tucker, Larry Lawson, Randall Gemmen
U.S. Department of Energy,
National Energy Technology Laboratory
3610 Collins Ferry Road
Morgantown, WV 26507-0880

ABSTRACT

Air flow management and control in a fuel cell gas turbine hybrid power system is evaluated using the Hybrid Performance (Hyper) hardware simulation facility at the National Energy Technology Laboratory (NETL), U.S. Department of Energy. The Hyper facility at NETL is a hardware simulation of a fuel cell gas turbine hybrid power system capable of emulating systems in the range of 300kW to 900kW. The hardware portion is comprised of a modified single-shaft gas turbine, a high performance exhaust gas recuperator, several pressure vessels that represent the volumes and flow impedances of the fuel cell and combustors, and the associated integration piping. The simulation portion consists of a real time fuel cell model that is used to control a natural gas burner which replicates the thermal output of a solid oxide fuel cell. Thermal management in the fuel cell component of the hybrid system, especially during an imposed load transient, is improved through the control of cathode air flow. This can be accomplished in a fuel cell turbine hybrid by diverting air around the fuel cell system. Two methods for air flow control are presented in the paper. In this paper, the use of bleed air by-pass and cold air by-pass are characterized quantitatively in terms of compressor inlet flow, process limits, system efficiency and system performance.

INTRODUCTION

Hybrid fuel cell turbine power systems have been identified by the National Energy Technology Laboratory (NETL), U.S. Department of Energy as a key enabling technology for achieving high efficiencies and low emissions in future power generation technology.[1]

The Hybrid Performance (Hyper) project has been commissioned by Office of Science, Technology, and Analysis at NETL to examine fundamental issues related to the dynamic operability of fuel cell gas turbine hybrid systems. The experimental facility is made available for public research collaboration with universities, industry and other research institutions. The Hyper project research objectives have been described in some detail previously[2]. The first objective is to investigate the steady and dynamic performance of a direct fired solid oxide fuel cell (SOFC) gas turbine (GT) hybrid system using hardware–in-the-loop methods. A flow diagram of the system being simulated is shown in Figure 1.

Managing cathode air flow during a load transient imposed on a SOFC/GT hybrid is critical to the operability of the power system. Any sudden reduction in load on the fuel cell would require a corresponding reduction in cathode cooling flow to prevent over-cooling the fuel cell which could lead to thermal fracture of the ceramic stack components. At the same time, the turbine in the system must deal with a sudden increase in thermal energy due to combustion of the increased amount of fuel passing unutilized through the fuel cell. This necessitates the use of a supplementary sink or source of energy to the hybrid plant in offsetting any transients, such as a resistive load bank on the fuel cell or turbine generator. A more practical solution is the implementation of by-pass valves to manage air flow in parallel flow loops while maintaining limits of the hybrid system components.

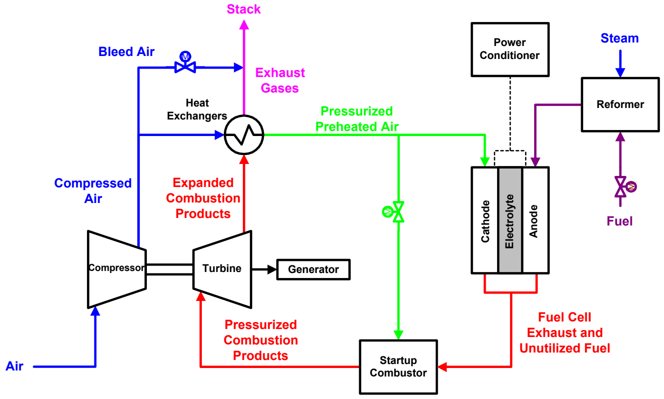

Figure 1
Simplified Flow Diagram of a Representative Direct Fired Fuel Cell Gas Turbine Hybrid System

The Hyper facility has been designed with three parallel air flow loops on the pressure side of the direct fired system: a hot air by-pass loop (FV-380), a cold air by-pass loop (FV-170), and compressor bleed air (FV-162). There were no valves placed in the main pressure loop between the compressor and the turbine to minimize pressure losses though the system. A flow diagram of the simulation facility is shown with pertinent valves and measured variables in Figure 2.

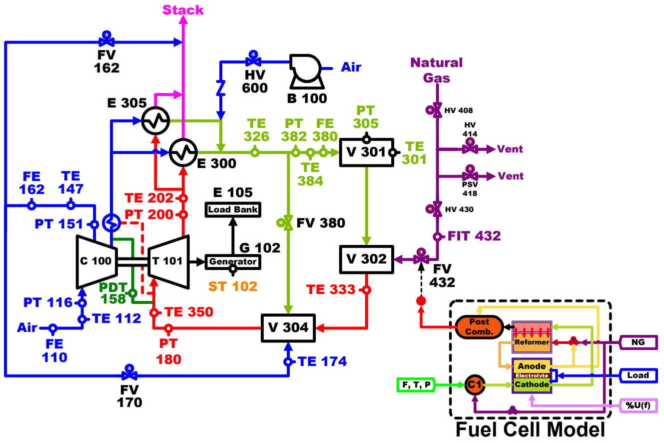

Figure 2
Simplified Flow Diagram for the Hybrid Simulation Facility at NETL

This paper reports on a study conducted using the Hyper Facility to characterize the changes in system performance in response to operation of both the cold air by-pass valve (FV-170) and the compressor bleed air valve (FV-162). The objective of the study was to identify potential methods for use in control strategies to regulate cathode air flow, absorb thermal transients, and mitigate risk of compressor stall and surge during operational transients.

EXPERIMENTAL METHOD

Approach

The change in system performance due to a change in by-pass flow is characterized here in terms of the change in air pressure drop and flow (air flow work), and change in input fuel flow rate. In order to separate various coupled phenomena, the present work assumes a fixed fuel cell operation in spite of any change in cathode flow, and employs a fixed gas turbine generator output of no electrical load. In principle, the latter could also be manipulated along with these by-pass flows to accommodate load transients, but the focus here is strictly on air flow behavior due to by-pass control.

Facility Description

The Hyper simulation facility uses a combination of hardware and real time dynamic models to simulate a solid oxide fuel cell gas turbine hybrid system.[3] A simplified process flow diagram of the experimental hardware simulation facility is shown in Figure 2. A real time fuel cell model was not used in the present series of experiments because characterization of the valve operation was conducted with the assumption that the fuel cell remained unchanged in thermal energy output during any change in air flow. The assumption here is that regardless of cathode flow to the fuel cell, the fuel cell operation is fixed and can be analyzed without a real time fuel cell model.

Ambient air from the large test cell is compressed and passes over the scroll in the compressor plenum (C-100) before exiting two discharge ports. For one discharge port, the compressed air is directed by valving to the turbine inlet (FV-170) or the system exhaust manifold and stack (FV-162). For the other discharge port, the air is directed without valving through the annulus portion of a tee for passage to recuperators and fuel cell plenum. This primary extraction air is routed through system piping to the heat exchangers (E-300 and E-305) for recuperation of turbine exhaust gas heat. This will be referred to as the *primary air loop*. The compressed, pre-heated air exiting the heat exchangers is expanded into a pressure vessel with a volume representative of the cathode volume of a 250kW tubular solid oxide fuel cell and the associated air distribution manifold (V-301). The discharge of the pressure vessel passes through a natural gas combustor (V-302) which provides the heat requirements via fuel flow rate specification of the fuel cell model, when used, or a speed control algorithm as described in the following subsection. The heated effluent of the combustor is expanded into another pressure vessel (V-304) with volume representative of the post combustor where residual fuel cell fuel is burned. This post combustor also serves as the mixing chamber for combustion products and recovered hot and cold by-pass air streams before final expansion through the turbine (T-101). The hot turbine exhaust is piped through the heat exchangers to the exhaust manifold and stack.

Auxiliary Power Unit (C-100, T-101, G-102)
A 120kW Garrett Series 85 auxiliary power unit (APU) is used for the turbine and compressor system. The APU consists of single shaft, direct coupled turbine (T-101), a two stage radial compressor (C-100) and gear driven generator (G-102). It was designed to deliver a high flow of compressed air for starting larger aircraft turbines, and is outfitted with a 120 kW, 400 Hz generator to deliver electrical power. The 400 Hz generation frequency used by the military aircraft sector reduces the weight of speed reduction gearing, generator and transformer iron. Typical APU applications do not require multiple unit synchronization thus relaxing the grid frequency regulation. The electrical generator is loaded by an isolated 75kW resistor bank (E-105) in the Hyper facility sufficiently sized to allow frequency excursions during transient load studies. The compressor is designed to deliver approximately 2 kg/s at a pressure ratio of about four. The compressor discharge temperature is typically 475K (395ºF) for an inlet temperature of 298K (77ºF).

The turbine was originally designed to operate on jet fuel. The OEM fuel system and combustor were removed and replaced with an insert modification (E-001) designed to both extract air from the compressor plenum, and direct the hot gases from the fuel cell simulator back into the turbine scroll. The compressed air must be extracted concentrically at the same point as hot gas injection to maintain cooling flow for the insert and turbine scroll.

Finally, during the testing of the two by-pass modes reported here, the turbine was operated without electric load and at a constant turbine speed which is attained by a speed integral feedback control action on fuel valve demand.

Heat Exchangers (E-300 and E-305)
The project facility makes use of two counter flow heat exchangers (E-300 and E-305), Solar Turbines Primary Surface Recuperators (PSR33), to preheat the air going into the pressure vessel used to simulate the fuel cell cathode volume.[4] Two PSR33s connected in parallel are required to handle the maximum compressor flow rate at the nominal pressure ratio. The maximum operating temperature on the exhaust side is limited by restrictions on the turbine exhaust gas temperature to 910K (1180ºF). The maximum observed operating temperature on the pressure side of the heat exchangers is limited to 780K (940ºF).

Pressure Vessels (V-301 and V-304)
Pressure vessels are used to provide the representative fuel cell air manifold and cathode volume (V-301), and the post combustion volume (V-304) of a solid oxide fuel cell. The residence time associated with these volumes are physically replicated. The vessels were designed to facilitate changes in the volumes to accommodate other fuel cell designs. The volume of the air plenum, V-301, and the associated piping is 2.0m^3. The cold volume of the post combustor, V-304 and associated piping is 0.78m^3. This is increased to 0.79m^3 under maximum operating temperature and pressure. The vessel and piping is fabricated from 2.54cm Incaloy 800AT, and is designed to operate at temperatures as high as 1200K (1700ºF) at a pressure of 310kPag.

Fuel Cell Simulator (V-302)
The thermal characteristic of the effluent exiting the post combustor of an SOFC system is simulated using a natural gas burner with an air cooled diffusion flame. The combustor is situated in a 19.4cm inside diameter (ID) schedule 80 Incaloy 800AT pipe welded directly to the inlet nozzel of the post combustor. Reformer fuel input and fuel cell electrical load conditions are specified for use in the model. In fuel cell simulation mode, the calculation for fuel demand is made using a 1D fuel cell model that operates in real time on the control platform to drive the natural gas combustion supply valve (FV-432). During the test conducted for this study, the burner was controlled by the speed control algorithm since airflow characterization was made at quasi-steady fuel cell conditions.

Bleed Air By-Pass Valve (FV-162)
The bleed air by-pass valve, FV-162, is used to bleed air discharge from the compressor plenum to the system stack. The valve is a nominal 15.4cm inside ID Valteck ShearStream control valve, and has a full range slew rate of about 1.5s. Compressor bleed provides an additional source of load to the turbine and reduces the total mass flow through the turbine, fuel cell simulator and the heat exchangers.

Cold Air By-Pass (FV-170)
The cold air by-pass valve, FV-170, is used to direct compressor discharge into the post combustor prior to the turbine inlet, by-passing the remainder of the primary system. FV-170 is a nominal 15.4cm ID Fisher-Rosemont V-150 Vee-Ball control valve with a full range slew rate similar to FV-162.

Hot Air By-Pass (FV-380)
Primary air flow through the pressure vessels used to simulate the cathode volume can be diverted using the hot air by-pass valve, FV-380, a nominal 15.4cm ID Valteck MaxFlow V-300 eccentric plug rotary control valve. The valve is designed for pressure operation at temperatures in excess of 810K (1000ºF), and has a full range slew rate of about 2.0 seconds. The function of FV-380 is to balance flow across the air plenum and fuel cell simulator. This control valve can be used to maintain constant air flow across the fuel cell simulator during the operation of other air valves.

Control Systems
An Atlas control system manufactured by Woodward Industrial Controls is used to control the Swift valve (FV-432) metering fuel flow to the system combustor. The swift valve is a 2.54cm sonic needle and nozzle operated at high speed with a stepper

motor capable of implementing fast natural gas flow changes. The control software used for the Atlas control computer incorporates MATLAB Simulink models developed at NETL for simulating thermal transients of fuel cell dynamics.[5] Turbine rotational speed is controlled with proportional, integral and derivative (PID) demand for fuel valve using feedback from optical speed instrument (ST-502). Many process variables of the Hyper facility are dependent on the speed of the turbine and are recorded within the turbine control system. All three by-pass valves are also controlled through the Atlas system as are all independent process variables of the hybrid facility.

An APACS system manufactured by Moore Products, Ltd. is used for burner management and protection of system equipment through a series of operational interlocks. This safety system is described in more detail elsewhere.[6] Most of the process temperatures are record in the APACS at 400ms intervals. A QUADLOG system manufactured by Moore Products, Ltd. is used as the primary safety system, and insures that the appropriate purge cycles are completed before ignition, and that the turbine inlet gases are vented to the stack in case of turbine over speed.

Instrumentation

There are 104 process variables measured in the Hyper facility, recorded at rates varying from 42μs to 400ms. The data presented was recorded using the APACS control system at 400ms intervals. A complete description of the facility and total instrumentation is published elsewhere.[6]

Rotational Speed Measurement (ST-502)

Rotational speed is measured by an optical sensor (ST-502) which picks up laser light reflected from a rotating target on the end of the generator shaft and transmits the pulse train to the frequency input of the Atlas control system. The optical sensor provides a 1,200Hz signal at the nominal 40,500 rpm turbine speed with observed standard deviation in measurements of 50 rpm or 0.12% relative error in the precision of the measurement. The dynamic range of the speed variable is 1,000 to 50,000 rpm.

Compressor Inlet Flow (FE-110)

Compressor Inlet Flow is measured using a Dieterich Standard Mass ProBar® annubar flow element (FE-110) which provides a mechanical average of the difference between stagnation pressure and static pressure in the inlet pipe to determine flow. The inlet pipe is 30cm inside diameter with 3.1m upstream and 2.4m downstream of FE-110 to provide fully developed flow. Verification of measurements with a hot wire anemometer required a 20% correction factor to flow data collected by the annubar. Time averaged data of compressor inlet flows at nominal speed indicate a 2.04kg/s average with a standard deviation in measurements of 0.020kg/s or 0.99% relative error in the precision of the measurement. Compressor inlet temperature (TE-112) and pressure (PT-116) reflect ambient conditions in the facility test cell during operation. The relative error in the precision of the measurements of the temperature and pressure was found to be 0.15% and 0.24% respectively. The ambient absolute pressure of the facility bay was measured using PT-003, and was used for pressure ratio calculations. The relative error in the precision of this measurement was found to be 0.18%.

By-Pass Flow (FE-162)

Compressor bleed air flow is measured using an annubar flow meter (FE-162) similar to FE-110. It is situated in a 15cm inside diameter pipe routed to the system exhaust manifold and stack as shown in Figure 2. For a time averaged flow of 1.1kg/s, the standard deviation in the measurements was found to be 0.016kg/s or 1.5% relative error in the precision of the measurement. Compressor discharge temperature (TE-147) and pressure (PT-151) are measured in the compressor plenum, just after diffuser and before air flow has circulated around the turbine scroll. The relative error in the precision of the measurement of the temperature and pressure was found to be 0.08% and 0.29% respectively.

Fuel Cell Simulator Flow (FE-380)

Primary air flow through the fuel cell simulator is measured at the entrance of V-301 using an annubar flow meter (FE-380) similar to FE-110. It is situated in a 15cm inside diameter pipe routed through V-301 and V-302 to V-304. For a time averaged flow of 1.55kg/s, the standard deviation in the measurements was found to be 0.011kg/s or 0.70% relative error in the precision of the measurement. The combined temperature of the mixed streams from the heat exchangers (TE-326) is measured just up stream of the hot air by-pass valve, FV-380 and was found to have a relative error of 0.01% during a run with an average temperature of 670K. Pressure is measured inside the air plenum of the fuel cell simulator (V-301) using PT-305, and was found to a relative error in the precision of the measurement of 0.27% during a typical test.

Turbine Inlet and Outlet Conditions

Turbine inlet conditions are measured using PT-180 for pressure and TE-350 for temperature. The turbine outlet conditions are measured using PT-200 for pressure and TE-202 for temperature. The relative error for these measurements was found to be 0.18% (TE-350) and 0.12% (TE-202) for temperature, and 0.29% for both pressure transducers. The original APU control system incorporated a turbine exhaust gas temperature (EGT) controller which takes priority over the combustor firing rate to protect the equipment from overload. The Hyper facility incorporates EGT limiting strategy to be further described below in the Test Procedure.

Test Procedure

The test procedure for system startup is discussed in detail elsewhere.[7] Compressor inlet conditions between testing of separate valves varied with the normal seasonal ambient conditions in temperature, pressure and humidity. Because the daily variation in ambient conditions was found to have an effect on process measurements, a baseline condition without any by-pass operation was established for each set of tests conducted on a single day. All tests for characterization of an individual valve were completed in a single day, without electric generator load.

As explained previously, since air flow management was evaluated at steady conditions, the fuel cell model was not used to control fuel flow to the simulator. Speed was maintained at nominal conditions throughout the tests by the controller, unless the EGT limit was reached. This EGT limit occurs only during the use of compressor bleed air and is indicated by a reduction in fuel flow and corresponding decrease in turbine rotational speed. The speed set point is suspended while the control system reduces fuel demand to limit EGT excursions above 863K (1090ºF). This reduction of speed below nominal during a steady state test is used as indication of the limiting constraint of by-pass flow. This limit occurred for a bleed air by-pass (FV-162) valve position of 22%, representing flows equivalent to 22.9% of compressor inlet flow. A valve position of representing a flow equivalent to 20.8% of compressor inlet flow was the maximum flow achieved without exceeding the EGT limit.

Operational constrains were also in effect for the implementation of cold air by-pass flow. Since the use of cold air by-pass reduces cooling flow through the system combustor without reduction of flow through the turbine, burner temperature limits could be exceed without reaching EGT limits. To avoid this, equivalence ratio was calculated from fuel and air flows (FT-432 and FT-380 respectively), and monitored during the test. Temperature measurements were impractical due to flame instabilities in the combustion zone at low cooling flows. If the equivalence ratio were to exceed 0.40, the test was terminated. This limit did not occur during the cold air by-pass test. The highest equivalence ratio reached was 0.31 at a 100% open setting representing a by-pass flow equivalent to 61.7% of compressor inlet flow.

Compressor Bleed Air Testing

The tests were initiated by starting the system with a compressor bleed air valve setting of 16% (8.9% of compressor inlet flow at nominal speed) to provide an initial preheat of system equipment. The system was allowed to come to a steady condition, defined as the heat exchanger exit temperature on the pressure side (TE-326) remaining constant within a relative change of 0.1K (0.2ºF) for a 28s time period. The initial steady condition required approximately 40 minutes. Each steady condition thereafter required between 10 and 20 minutes. When a steady condition was reached, it was maintained for a minimum of 3 minutes before any further change in process conditions was made. A complete plant-wide steady state requires all piping skin temperatures to also come to an equilibrium, which requires approximately four hours.

After completion of the startup, the compressor bleed was closed and the system was allowed to cool to a steady condition as previously defined. The compressor bleed air valve (FV-162) was then opened to 8% for the first test and allowed to come to a steady condition. All other by-pass valves were closed during this test. The valve was incremented by 2% from 8% to 20%, and incremented by 1% from 20% to 23%. At each increment, the system was allowed to come to a steady condition. The relevant time series data is shown for selected process variables below in Figures 3 and 4.

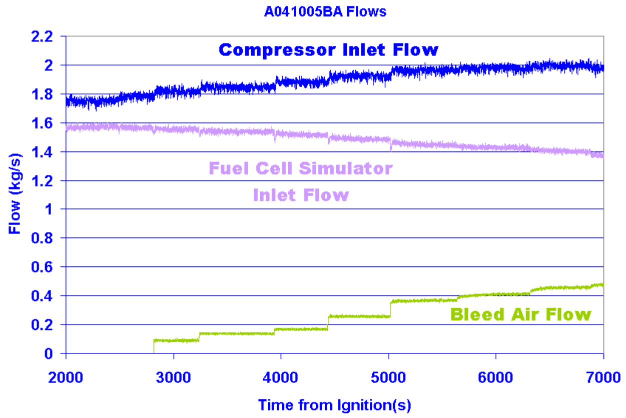

Figure 3

Raw Time Series Flow Data for Compressor Bleed Air Tests

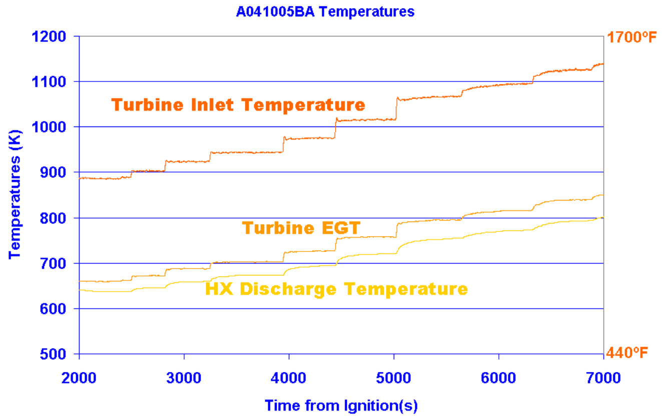

Figure 4

Raw Time Series Temperature Data for Compressor Bleed Air Tests

Cold Air By-Pass Testing

The tests were initiated by starting the system with all by-pass valves closed. The system was allowed to come to a steady condition as defined previously for the compressor bleed air test. As with the previous test, the initial steady condition required approximately 40 minutes. Each steady condition there after required between 10 and 15 minutes. Temperature changes were less dramatic during tests with the cold air by-pass, and required slightly less time to achieve equilibrium. When a steady condition was reached, it was maintained for a minimum of 2 minutes before any further change in process conditions was made.

The cold air by-pass valve (FV-170) was then open to an initial setting of 10% for the first test and allowed to come to a steady condition. The valve was incremented by 5% from 10% to 100%. The system was allowed to come to a steady condition at each valve position. The relevant time series data is shown for selected process variables below in Figures 5 and 6.

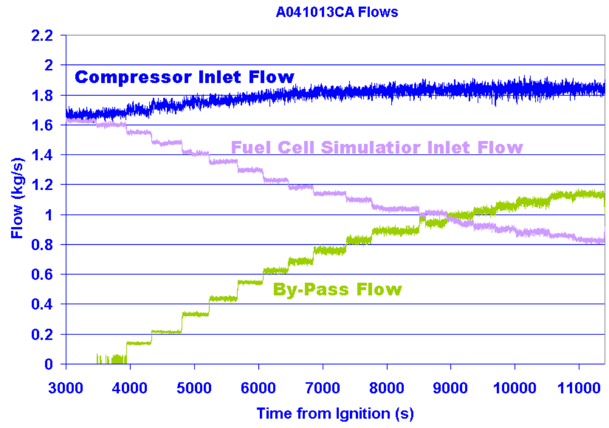

Figure 5
Raw Time Series Flow Data for Cold Air By-Pass Tests

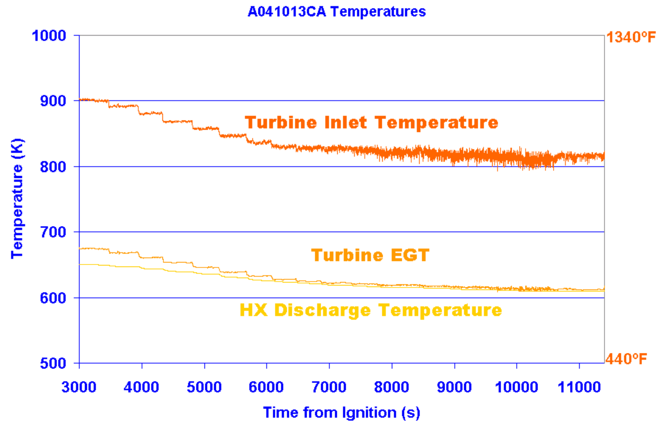

Figure 5
Raw Time Series Flow Data for Cold Air By-Pass Tests

RESULTS

Compressor Bleed Air

The impact of implementing compressor bleed air on the compressor inlet flow and flow to the fuel cell cathode is shown as a function of the flow by-passed in Figure 7. Data symbols represent steady state, time averaged values for each condition as described previously. Compressor inlet flow is increased from 1.75kg/s to 2.00kg/s, or 14% over the full range of 0.46kg/s compressor bleed. The air flow directed to the cathode volume of the fuel cell is reduced from 1.57kg/s to 1.40kg/s, or 11% over the full range of bleed air.

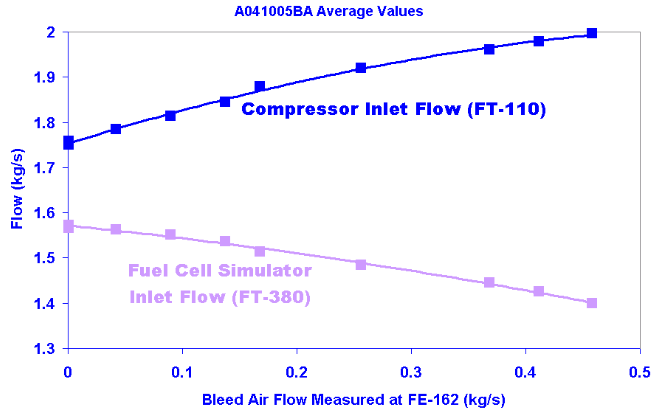

Figure 7
Averaged Data for Compressor Inlet Flow and Fuel Cell Simulator Flow Expressed as a Function of Bleed Air Flow

The effect of compressor bleed on system pressures and overall pressure drop is shown below in Figure 8. The total system pressure drop is affected only at higher compressor bleed flows, but is reduced from 50.6kPad to 49.2kPad, or 3% at the maximum compressor bleed. Both compressor discharge pressure and turbine inlet pressure are reduced by about 5% over the entire range of compressor bleed flow.

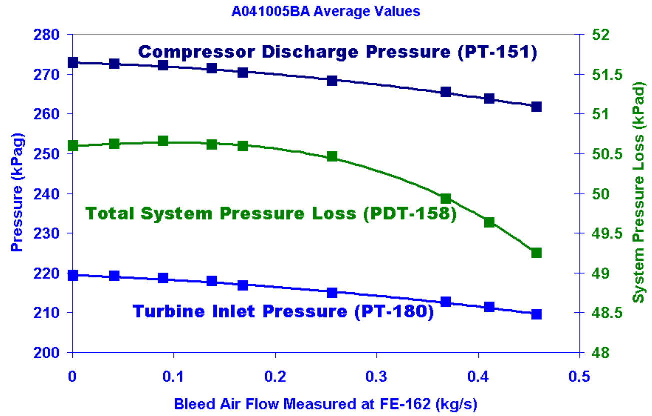

Figure 8
Averaged Data for Compressor Discharge Pressure, Turbine Inlet Pressure and Total System Pressure Drop Expressed as a Function of Compressor Bleed Air Flow

The overall reduction of compressor discharge pressure shown in Figure 8 and the increase of compressor inlet flow indicated in Figure 7 provide a clear indication that bleed air can be used as an effective means of increasing the compressor surge margin during operations to avoid stall. The limited reduction in flow to the fuel cell cathode over the full range of compressor bleed implementation (~11%) reveals the method as a poor means of managing cathode air flow requirements.

The impact to system temperatures and fuel requirements by compressor bleed is illustrated in Figure 9. As expected, the turbine inlet temperature (TIT), turbine exhaust gas temperature (EGT) and heat exchanger discharge temperature all increased with increasing compressor bleed air flow, indicative of wasted turbine work to drive the bleed air compression work. Both TIT and EGT are increased by 27% over the full range bleed air mass flow. The heat exchanger discharge temperature is increased by 24%. The increased requirement for shaft load due to compressor work is reflected in the 39% increased fuel requirement.

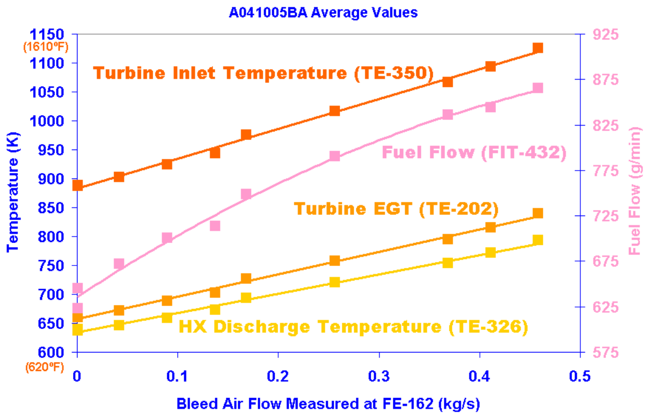

Figure 9
Averaged Data for System Temperatures and Fuel Flow Required for Constant Turbine Speed Expressed as a Function of Compressor Bleed Air Flow

The significant increase in turbine thermal input indicated by fuel demand suggests that the application of compressor bleed air can also be effective in managing a significant transient increase in thermal energy to the turbine in a hybrid configuration (e.g., due to sudden fuel cell load loss). There remains the risk of a sudden cooling on the fuel cell, but it is clear that the other hardware components are not at risk.

Cold Air By-Pass

The implementation of cold air by-pass method on system compressor inlet flow and flow to the fuel cell cathode is shown as a function of the flow by-passed from compressor to turbine in Figure 10 below. Compressor inlet flow is increased by 10% over the full operating range of the valve, and exhibits diminishing returns at high mass flows of by-passed air. The air flow directed to the fuel cell cathode is reduced by 49%, showing the method to be effective in managing cathode air flow during load changes up to about 50%.

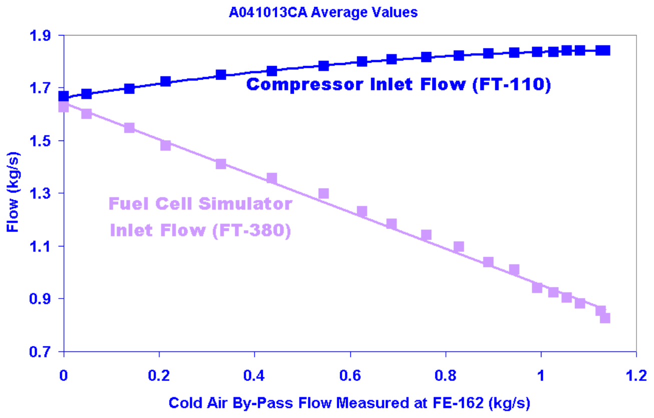

Figure 10
Averaged Data for Compressor Inlet Flow and Fuel Cell Simulator Flow as a Function of Cold Air By-Pass Flow

The effect of cold air by-pass implementation on system pressures and system pressure drop is shown below in Figure 11. During cold air by-pass operation, a significant decrease (70%) in system pressure drop is observed. While compressor discharge pressure does decrease, as in the case for compressor bleed air, turbine inlet pressure actually increases by 11% over the operating range of the cold air by-pass valve.

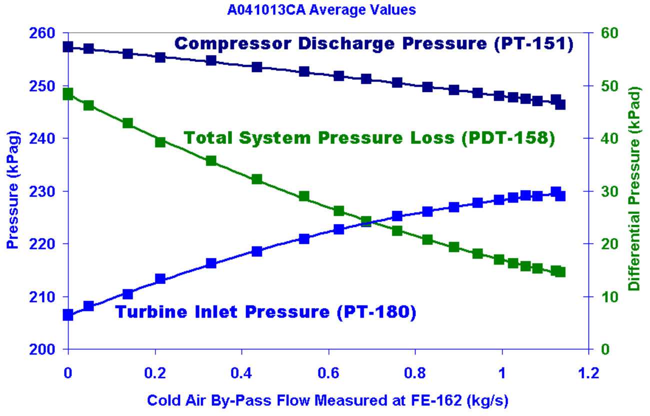

Figure 11
Averaged Data for Compressor Discharge Pressure, Turbine Inlet Pressure and Total System Pressure Drop Expressed as a Function of Cold Air By-Pass Flow

As is the case for compressor bleed air use, application of the cold air by-pass during operations results in decreased compressor discharge pressure and increased flow, indicating a corresponding improvement in the surge margin.

The effect of cold air by-pass implementation on system temperatures and required fuel flow for constant rotational speed is shown in Figure 12. In the use of cold air by-pass operation, turbine inlet temperature and turbine exhaust gas temperature are decreased by 9.5% and 9.3% respectively over the entire range of operation. The heat exchanger discharge temperature is reduced by only 6.4%. This is caused primarily by the increased ratio of exhaust flow to compressed air flow though the heat exchangers, resulting in an ever decreasing discrepancy between the heat exchanger discharge temperature and the EGT. The fuel requirements are increased by a total of 19.6%, indicating an increase in compressor shaft load with increased total inlet flow at high cold air by-pass flows. The gradual fall-off in fuel required at mid-range by-pass flows is due primarily to the improvement in system pressure drop, reduced compression work and increased turbine mass flow offsetting the decrease in turbine inlet temperature.

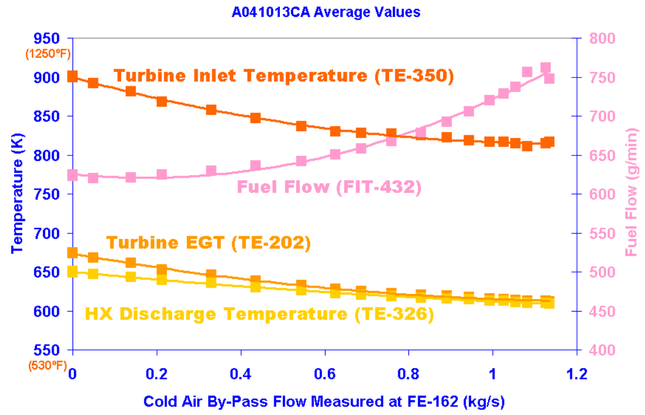

Figure 12

Averaged Data for System Temperatures and Fuel Flow Required for Constant Turbine Speed Expressed as a Function of Cold Air By-Pass Flow

The smaller increase in fuel demand with increasing cold air by-pass flow shows less promise than compressor bleed air as a strategy for absorbing thermal transients. If cold air by-pass is used exclusively as a control method for a load trip, an increase in turbine thermal input due to loss in fuel cell load will cause the turbine to speed up, and this will result in an increase in cathode flow which is precisely the opposite to what is needed to protect the fuel cell from excessive cooling. The lower fuel requirement for large changes in cathode air flow, however, does indicate the effectiveness that the cold air by-pass has in managing fuel cell cathode air flow without a substantial sacrifice in system efficiency.

Comparison

A comparison is made of the two strategies with regard to system pressure drop in Figure 13. System pressure loss is plotted in terms of a percent of compressor discharge pressure against the mass flow of compressor air by-passed (CA) or bleed (BA). It is clear from the illustration that the use of cold air by-pass is far more effective in reducing system pressure drop, and hence improving compressor surge margin.

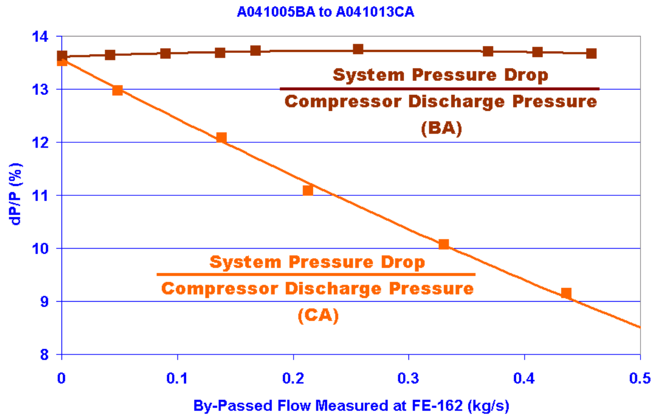

Figure 13

A Comparison of System Pressure Loss as a Percent of Total Compressor Discharge Pressure Expressed as a Function of Flow Either Bled (BA) or By-Passed (CA)

A comparison is made in Figure 14 for the two air flow strategies presented of fuel requirements for flow achieved in terms of initial fuel required for the base condition of each test. Compressor bleed air is shown to require a much greater specific energy requirement, while cold air by-pass is shown to have an insignificant specific energy requirement over the same operable range of flows.

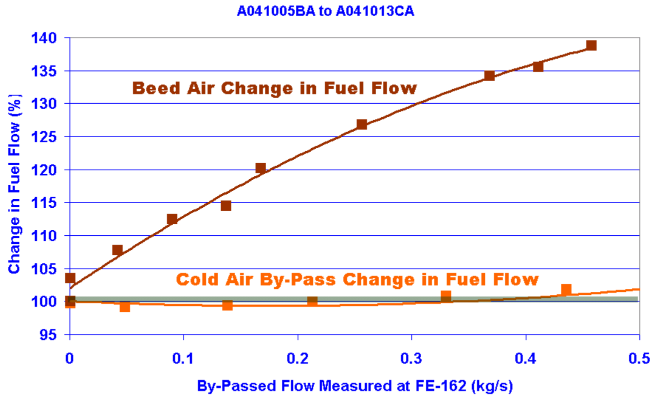

Figure 14

A Comparison of Percent Change in Fuel Required for Constant Turbine Speed as a Function of Air Flow Bled or By-Passed

CONCLUSIONS

Tests were conducted using the Hyper experimental facility at NETL to characterize the implementation of compressor bleed air and cold air by-pass as methods for manipulating hybrid system process variables through air flow management. The cold air by-pass was found to be effective in diverting substantial fuel cell cathode air flow (49%), with only a moderate impact to system efficiency (19.6% increase in required fuel over base case). For by-passed flows representing less than 25% of compressor inlet flow, cold air by-pass operation did not require any significant increase in energy. The cold air by-pass was also shown to be an effective method to increase the operating surge margin, and avoid compressor stall.

The use of compressor bleed air was found to be an effective method for increasing shaft load and absorbing thermal transients with reduced by-pass flow. An increase in fuel requirements of 39% was required for a bleed air flow equivalent to 20.8% of the compressor inlet flow. This indicates potential for system control during fuel cell load loss or reduction. Compressor bleed air was also shown to be an effective means to increase the compressor surge margin. The method was limited because by-passed flows beyond 22% of compressor inlet air could not be sustained without exceeding the EGT constraint.

The data presented provide the first qualitative steps in characterizing possible control methods for hybrid fuel cell gas turbine power systems using compressed air flow management with valves only in cold-service side streams. The use of compressor bleed air and cold air by-pass simultaneously offer the potential for system control though a variety of transient scenarios. The methods studies show promise for effective control of a hybrid system without the direct intervention of isolation valves or check valves in the main pressure loop of the system, which introduce substantial pressure losses. The elimination of such measures for protection and control during transient operation would allow for the full potential efficiency of the hybrid system to be realized.

Future work will include the characterization of the hot air by-pass and a more complete analysis of the application of these methods in transient control strategies.

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REFERENCES

1 Dennis, R. A.; Samuelsen, G. S.; Williams, M. C.; Holcombe, N. T.; Layne, A. W. “The National Energy Technology Laboratory's Hybrid Power Systems Program,” 2002 ASME Turbo Expo, Amsterdam, The Netherlands (GT-2002-30668).

2 Tucker, D.; Liese, E.; VanOsdol, J. G.; Lawson, L. O.; Gemmen, R. S. "Fuel Cell Gas Turbine Hybrid Simulation Facility Design," 2003 ASME International Mechanical Engineering Congress and Exposition, New Orleans, LA.

3 Tucker, D.; Lawson, L. O.; Gemmen, R. S. “Preliminary Results of a Cold Flow Test in a Fuel Cell Gas Turbine Hybrid Simulation Facility,” 2003 ASME Turbo Expo, Atlanta, GA, USA (GT2003-38460).

4 Ward, M. E. and Stephenson, M. D. “The Primary Surface Recuperator- Durability and Applications,” International Gas Turbine Congress 1999, Kobe, Japan.

5 Shelton, M. S.; Liese, E.; Tucker, D.; Celik, I.; Lawson, L. O. “Fuel Cell/Gas Turbine Transients- A Study in Process Modeling Using Simulink Modeling of a Hybrid Test Facility,” 2005 ASME Turbo Expo, GT2005-68467.

6 Tucker, D.; Liese, E.; Lawson, L. O.; Gemmen, R. S.; Shelton, M. S.; Ruehl, D. “Technical Description of the Hybrid Performance Project Test Facility and System Model,” U.S. Department of Energy Technical Note (In Press).

7 Tucker, D.; Lawson, L. O.; Gemmen, R. S. “Evaluation of Hybrid Fuel Cell Turbine System Startup with Compressor Bleed,” 2005 ASME Turbo Expo, GT2005-68784.