Federal Energy Technology Center ATS Research

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1 Introduction

The Combustion and Engine Dynamics Division at the Federal Energy Technology Center conducts applied and exploratory research aimed at developing flexible, low-emission energy systems. Using a variety of arrangements, research activities can be conducted in partnership with small businesses, turbine vendors and suppliers, universities, and government labs. This paper reviews the results of emerging activities that support hybrid fuel cell/gas turbine systems, as well as ongoing developments in low-emission combustion. We present the following topics:

- Development of a test stand to evaluate the integration issues associated with combining a fuel cell and a gas turbine.
- Results of combustion studies to support humid air turbine (HAT) cycles.
- Evaluation of a dual-fuel, low-emission fuel injector.
- Experimental tests of "active" combustion control on a full turbine engine.

A parametric study of the effect of fuel injector design on combustion stability, combining experimental results and numeric simulation.

2 Hybrid Test Stand Development

The U.S. Department of Energy (DOE) has begun to focus on integrating fuel cell and gas turbine hybrid systems. The integration of these two technologies is expected to provide superior energy efficiency and environmental performance. To date, these two major subsystems have been largely developed and optimized by separate developers for independent commercialization. Hence, one of DOE's initial goals is to bring these two industries together for cost-effective development of the hybrid technology. Progress in this area has been made through recent Program Research and Development Agreements (PRDAs), where overall system concepts have been proposed. We anticipate that these cooperative efforts will continue to evolve as each developer pursues its proprietary position on hybrid technology.

Another government goal is to achieve increased participation by the technical community (university, government, and industry) in developing hybrid systems, and to increase our knowledge base on the technology. As part of the effort to achieve this goal, FETC is developing a hybrid test stand to assess and report on research and development (R&D) needs in the generic hybrid technology. In addition, new dynamic modeling tools are being developed to improve performance predictions, and to help provide better understanding of the operational behavior of these new systems. This latter work has already begun in partnership with the National Fuel Cell Research Center at the University of California, Irvine. Ultimately, the newly developed tools and knowledge base from this activity will be incorporated into DOE's Vision 21 program and virtual demonstration support technology.

This type of in-house activity continues a government role in R&D similar to that established in other research programs, specifically, the Advanced Turbines Systems (ATS) Program. FETC in-house researchers have performed independent R&D and cooperative research with industry, and have provided additional guidance to FETC management on technology R&D needs.

2.1 Test Stand

Progress in hybrid development has been inhibited by the high cost and limited availability of fuel cells. To move development forward, we will use a fuel-cell simulator in the test stand. The role of the fuel cell simulator is to provide a gas volume, flow resistance, and an exhaust temperature and pressure that are representative of a real fuel cell when integrated with a gas turbine. For the test stand to achieve a sufficiently accurate representation of a hybrid plant's dynamic behavior, the various time scales associated with the actual system need to be accurately represented.

Characteristic time scales of interest include: flow/pressure perturbation, thermal, chemical/electrochemical, and turbine-speed. These time scales and the character of the associated transients are dependent upon geometry, operating condition, materials, strength of the dissipation mechanisms, and any coupling or feedback processes.

Based on design data available in the literature (see following section), the basic geometry of a hybrid system can be estimated to preserve the relevant dynamic performance of a real system. Clearly, because the fuel cell is being simulated, the basic electrochemical time scale will not be represented. However, since this time scale is very short compared to the other time scales of interest, coupling between the electrochemistry and these other processes will not be significant. This means the electrochemical aspect can be achieved effectively simulated by a combustion process (to provide the necessary temperature to drive the gas turbine), while the other dynamic aspects of the hardware remain relevant.

This approach enables many of the dynamic aspects of the hybrid system to be represented. However, a real-time model of the fuel cell will be incorporated so that perturbations such as fuel cell "trips" can be evaluated. This will provide control input to the simulated fuel cell combustor. For example, when a fuel cell trips, it may take time for the gas supplies to be reduced. During this time, there may be a significant temperature rise as the fuel and air entering the fuel cell now exit as products of combustion. The fuel-cell-simulator's fuel controller can be programmed to respond to such a perturbation, making it possible to determine any effects.

2.2 Test Stand Design Data

Data can be found in journal and patent literature that describe the basic geometry and operating conditions of hybrid systems, whether for molten-carbonate or solid-oxide fuel cells. For example, Westinghouse Patent No. 5,413,879 describes one such system for solid-oxide fuel cells. Based on these data, reasonable assumptions, and data from other publications, nominal plant hardware can be described along with associated flow rates, pressures, and temperatures.

Our initial work involves the use of an AlliedSignal 75 kW auxiliary power unit (APU). (See Figure 1.) This turbine provides relatively easy access to the hardware necessary to take compressor air off the system and deliver hot gas to the turbine. The hybrid simulator test stand has been designed based on the nominal flow rates of this turbine and the design data for the hybrid system. Final construction will occur in 1999/2000; initial testing will help elucidate the dynamic behavior of this facility.

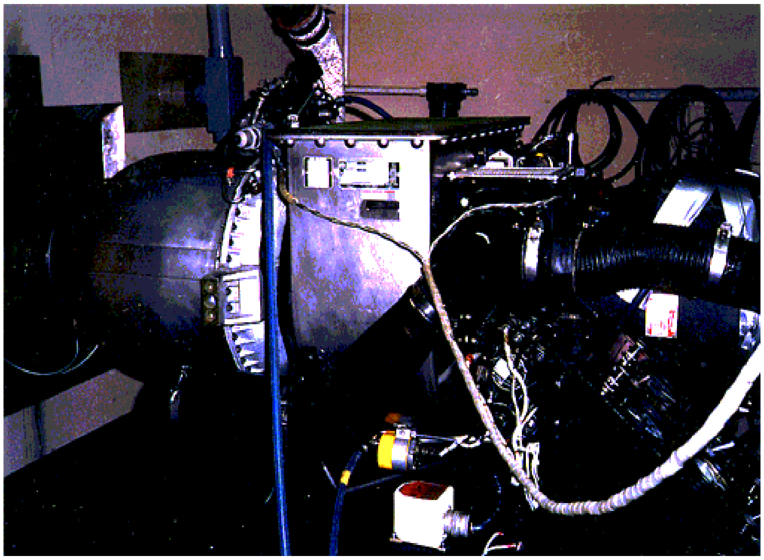

Figure 1. Hybrid Test Stand Auxiliary Power Unit
(photo taken while unit was being acceptance-tested by the vendor)

2.3 Model Development

The dynamic modeling tools being developed for hybrid systems will be used to support our in-house hybrid test-stand activity and to assess new control requirements and other technical needs for this technology. Progress in the development of these tools was presented at the 1999 International Gas Turbine Institute (IGTI) meeting (Liese et al. 1999). Other research activities include adding internal reforming within the fuel cell model, integrating the components within ProTRAX (a commercial dynamic simulation package for power plants), and simplifying the solution procedures. Results from this ongoing work will be presented at the 2000 IGTI meeting.

3 Humid Air Turbine Combustion Studies

Researchers are evaluating the humid air turbine (HAT) cycle as a possible low-emission, high-efficiency cycle for advanced power generation systems. Most of the previous investigations of this technology were primarily systems and modeling studies. Consequently, FETC has been working with the United Technologies Research Center (UTRC) and Pratt and Whitney to identify and address key R&D issues related to this advanced cycle. A joint experimental and modeling effort was initiated to examine the effects of combustion-air moisture content on emissions, stability limits, and ignition in gas turbine flames.

The Phase I study was completed last year, and results of that effort have been reported in some detail in a paper presented at Turbo Expo 99 (Bhargava et al. 1999) and in two papers submitted to Turbo Expo 2000 (Bhargava et al. 2000; Kendrick et al. 2000). The primary objectives of Phase I were to study the effects of:

- Combustion moisture on emissions, stability limits, and ignition behavior;
- Different nozzle designs on operating behavior; and
- Nozzle scale on combustion performance.

Nitrogen oxides (NO_X), carbon monoxide (CO), and unburned hydrocarbon (UHC) emissions and combustion stability were examined for varying levels of steam addition, system pressure, preheat temperature, equivalence ratio, pilot fuel level, and nozzle design and scale. Experiments were conducted in a hot refractory wall environment in the Low Emissions Combustor Test and Research (LECTR) facility at FETC. Results showed that when moisture is added, NO_X emissions are reduced significantly and CO levels tend to increase. In addition, the lean stability limit, indicated by the CO emissions, tends to move to richer conditions. Modeling results using a network of perfectly stirred reactors (PSRs), and the GRI Mech 2.11 kinetics and thermodynamic database (Bowman et al. 1994) showed good agreement with the experimental data over a wide range of conditions.

Phase II of this program is currently in progress and is expected to be completed by the end of fiscal year 2000. The objective of Phase II research is to examine different liner conditions and to study the effect on combustion operating characteristics. The two different liners to be studied include the refractory (approximately adiabatic) walls used in Phase I and a convectively cooled liner. As with Phase I, two different fuel nozzle concepts are being tested and compared. Experiments are being performed to characterize stability boundaries, emissions, and pressure dynamics at simulated part-power operating conditions.

4 Dual-Fuel Combustion Studies

In addition to achieving low pollutant levels in gaseous-fuel lean-premixed systems, many gas turbine installations must operate on both liquid and gaseous-fuels. These dual-fuel combustors must be flexible enough to burn different fuels without affecting combustor operability, while achieving very low pollutant emissions with both fuels.

A preliminary evaluation of a novel dual-fuel premixer was conducted as part of a FETC Cooperative Research and Development Agreement (CRADA). Parker-Hannifin Corporation has designed the prototype premixer. Parker-Hannifin is a leading manufacturer of fuel atomizers for gas turbine applications, and has recently patented a design and manufacturing technique called "Macrolamination." This technique allows complex internal flow channels to be formed by fabricating the fuel injectors in layers. The fuel-flow delivery channels, spin slots, swirl chambers, and the exit orifices are etched into thin substrates. These substrates are bonded together to fabricate fuel injectors, or fuel injector arrays with improved fuel-air mixing characteristics.

Parker-Hannifin's dual-fuel premixer concept has been tested at FETC. Both the emissions performance and the dynamic stability of this premixer have been assessed for various premixer configurations and different fuel-types. Natural gas and diesel fuel (Type-2) have been investigated. Results show that using the Parker-Hannifin premixer, NO_X and CO emissions of less than 20 ppm can be achieved with both fuel types at operating pressures and inlet-air temperatures of 5 atm and 533 K, respectively. The results also indicate that a simple time-lag approach typically used to correlate dynamic instabilities for gaseous-fuel applications also applies for liquid-fuel operation. These results are described in more detail in a paper submitted to Turbo Expo 2000 (Mansour et. al 2000).

5 Experimental Tests of "Active" Combustion Dynamics Control

Combustion oscillations (or dynamics) continues to be a challenging issue for the design of low-emission turbine combustors. Oscillations often complicate achieving emissions goals or limit engine capability for new fuels or new requirements. Although progress has been made in understanding and solving some classes of problems, a general approach to solving every type of oscillation does not yet exist.

The typical approach to addressing oscillations is to make design changes that reduce the combustion response (acoustic response) of the combustion chamber. (See the next section.) In contrast to design changes, an emerging technique called "active" dynamics control has been proposed by numerous investigators. In the usual proposal, control is achieved by pulsing the fuel to release heat out-of-phase relative to the oscillation, thereby reducing the cyclic heat release. This requires very high fidelity control of the fuel input.

Another approach, called periodic equivalence ratio modulation (PERM) has been studied in a CRADA between FETC and Solar Turbines. The PERM concept for single-injector applications is described in a paper by Richards, Janus, and Robey (1999). The concept is shown in a complete engine in Figure 2. The figure shows a map of oscillating combustion regions plotted against air flow and equivalence ratio (i.e., normalized fuel-air ratio). Adjacent injectors are modulated in and out of the oscillating region as shown. In this manner, the engine can be operated at a desired time-averaged equivalence ratio, but half of the injectors are operating at stable conditions at any instance in time.

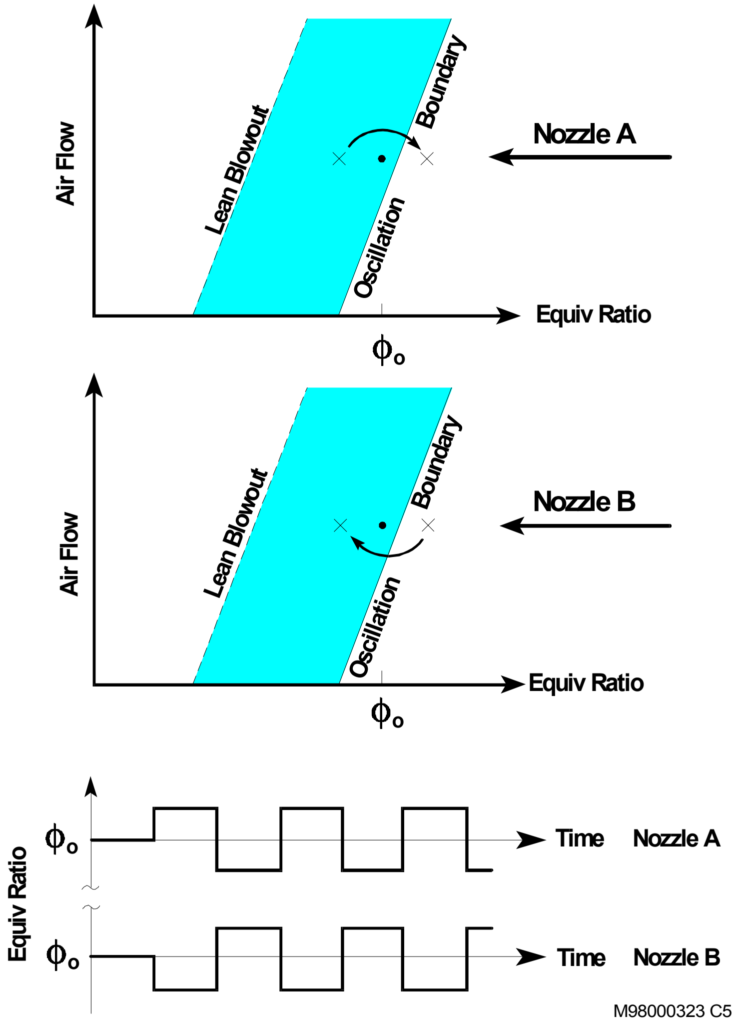

Figure 2. PERM Concept With Two Adjacent Injectors A and B in a Complete Engine

The PERM concept was implemented on a test engine having 12 individual fuel injectors. No modifications to the injector or engine hardware were needed. The control solenoids were commercial, reciprocating-engine fuel injectors, installed in the fuel-line branches supplying the individual fuel injectors.

The fuel was modulated as shown in Figure 3. The circles at the left show a schematic representation of how the injectors were modulated. The large circle, containing the six smaller circles, represents a view of the combustor along the flow path. The six pie-shaped segments indicate where the six injectors received increased fuel. By modulating the fuel, these segments were exchanged back and forth with adjacent injectors. Modulation was carried out at frequencies from 10 to 100 Hz without any noticeable effect on engine performance. However, a significant effect on the oscillations was observed. As shown at the right in Figure 3, the pressure history without PERM shows a strong oscillation (3psi peak-to-peak) at 300 Hz. When the control was activated as described, this oscillation was eliminated (lower figure).

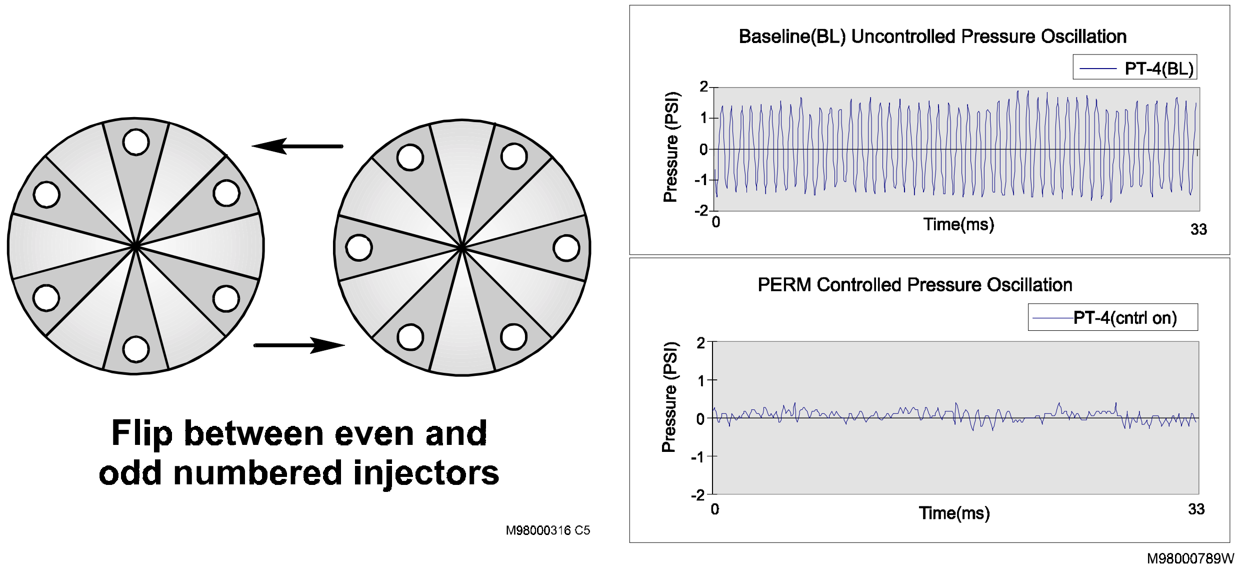

Figure 3. Schematic of Injector Modulation on a 12-Injector Engine (left), and Engine Pressure Signals (right) Without (upper) and With (lower) PERM Control

Pollutant measurements showed that the PERM concept could produce a significant increase in CO emissions, depending on operating conditions. NO_X emissions were not appreciably affected, typically increasing by 1 ppm during PERM control.

Additional tests have shown that PERM will not succeed in controlling all types of oscillations. We are currently working on understanding what class of problems can be successfully solved using the PERM concept.

6 Large-Scale Simulation of Combustion Dynamics

Considerable progress has been made in recent years in solving certain types of combustion dynamics problems. It is now well accepted that convective time lag in the premixer can sometimes be favorably modified to produce stable combustion (Richards and Janus 1998; Steele et al. 1999; Lieuwen et al. 1999). However, the role of fuel injector aerodynamics is not well understood. Tests conducted at FETC show that particular swirl vane configurations can enhance stability, but the details of how this improvement occurs are not understood. (See Straub and Richards 1999.)

In a partnership with FLUENT Inc. and the Pittsburgh Supercomputing Center, FETC researchers have been conducting very large-scale simulations of combustor/injector geometries that have been studied at FETC. These simulations use more than 750,000 grid points to model the reacting flow in a three-dimensional segment of the test combustor. Unsteady flow/combustion has been recorded for more than 50 milliseconds of real time, providing a complete record of how combustion proceeds from an assumed steady startup to either high or low amplitude oscillations. Figure 4 is an example of the convoluted flame surface that results as the oscillation occurs.

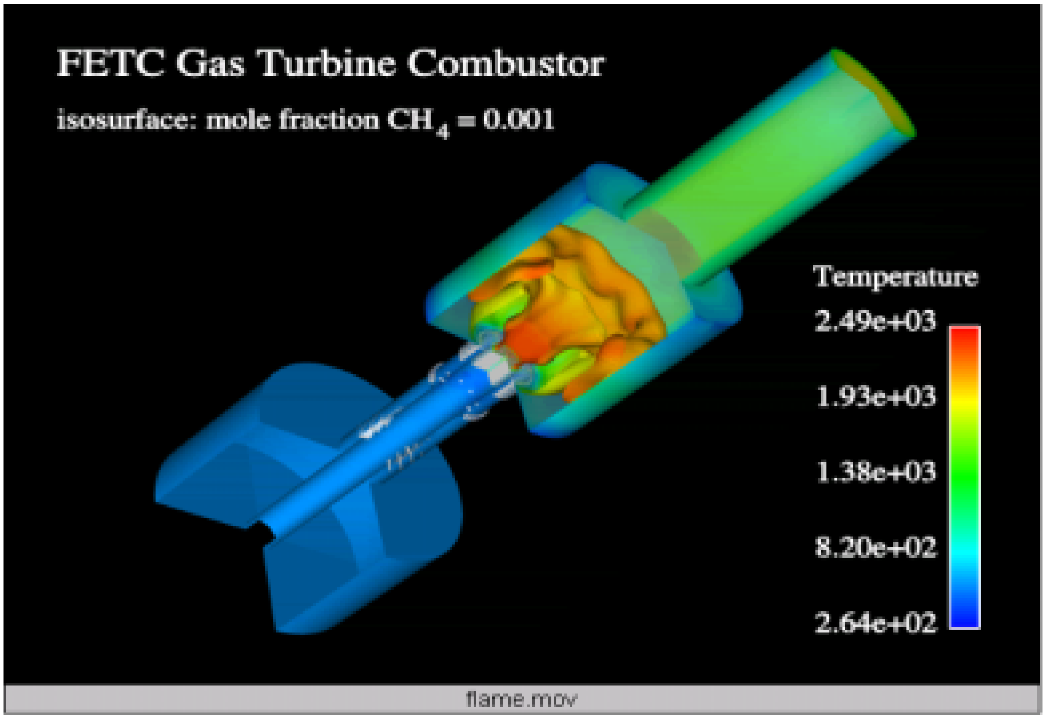

Figure 4. Unsteady 3D Simulation Results Showing Fuel Mole Fraction Isosurface Temperature

The results to date have shown that changes in the swirl vane configuration produce a sizeable change to the well-known premix time-lag. These changes may indicate that injector aerodynamics can be understood by simply quantifying the effect on the established time lag. Based on the simulation findings, we are attempting to validate a method to experimentally measure the changes in the time lag as a function of injector aerodynamics.

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