Pressure-Gain Combustion for Gas Turbines

Authors:
R. Gemmen
G. Richards
M. Janus

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ABSTRACT

As part of the Department of Energy's Advanced Gas Turbine Systems Program, an investigation has been performed to evaluate "pressure-gain" combustion systems for gas turbine applications. Results from the investigation have shown that, due to the oscillatory combustion process, a pressure boost can be achieved for suitable combustor geometries. The pressure gains achieved thus far have been as high as 1 percent. It has also been shown that for some combustor designs operating under typical gas turbine conditions, NOx and CO emissions are about 30 ppmv and 8 ppmv, respectively. It is believed that with optimized designs, further improvements in both pressure gain and emissions may be possible. We have concluded that this technology remains a candidate for improving the efficiency of a gas turbine while reducing pollutant emissions.

OBJECTIVES

This research supports the Department of Energy's Advanced Gas Turbine Systems Program. The goal of this program is to increase cycle efficiencies and to reduce pollutant emissions of utility and industrial gas turbine power generating systems. The objectives of the work reported here are to (1) determine how pressure gain can be achieved in combustion systems; (2) determine pressure effects for pressure-gain systems; and (3) evaluate their pollutant performance. Since such pressure-gain systems necessarily impose unsteadiness to the gas flow through a gas turbine, the ability to minimize such unsteadiness outside the combustor is also assessed.

BACKGROUND

Several investigators have studied combustion systems capable of producing pressure gain: Thring (1961), Porter (1958), and Kentfield (1988), to name a few. Designs have varied from piston-cylinder arrangements to those supporting a fluid mechanic resonance. In all cases, the fundamental feature that enables pressure gain to be achieved is the ability to burn fuel in a constant-volume manner. The closer a system imitates a constant-volume combustion process, the greater will be the achieved pressure gain during the combustion event. Hence, piston-cylinder combustion geometries can usually be expected to produce a greater pressure gain given their more constant volume combustion process, as compared to acoustic devices that experience greater volumetric expansion.

Figure 1 shows how the efficiency of a simple-cycle gas turbine can be increased with pressure gain. For a detailed theoretical analysis, see Gemmen et al. (1992). Here, the pressure gain is shown as percent increase from compressor exit stagnation pressure to turbine inlet stagnation pressure: \((P_c-P_i)/P_c*100\), where \(P_c\) is the compressor exit pressure, and \(P_i\) is the turbine inlet pressure. The figure is based on an analysis assuming thermodynamically ideal conditions for all components and a specific heat ratio of 1.4.
combustion rig as well as a pressurized combustion rig. Both systems have similar features, so only the atmospheric rig will be discussed here. A more detailed description of the pressurized rig has been reported (Gemmen et al. 1994). Figure 2 shows a typical configuration used for the atmospheric rig. Combustion air and fuel enter on the left at the inlet plenum. The combustion air enters directly into the inlet plenum, while the fuel is delivered to the combustor with typically a 1/8-inch diameter stainless steel tube. The combustion air and natural gas fuel mix inside the combustion chamber and ignite with the previous cycle’s exhaust products. (No ignition source is required except for start-up.) The exhaust products exit out of the combustor through a tailpipe and enter the dilution plenum where they mix with dilution air. From the dilution plenum, the gas passes out through an 8-meter exhaust duct to the atmosphere. Thermocouples are used for temperature measurement at several locations over the combustor for wall and gas temperatures. The dynamic pressure inside the combustor is measured using a Kistler model #206 transducer. For the atmospheric rig, mean pressure differences across the combustor (pressure gain) and from inlet plenum into the combustion chamber are measured using either a water manometer or a Setra model #226 low-differential pressure gage.

EXPERIMENTAL SETUP

Because resonating combustion systems can be designed without mechanically moving parts, our research has focused exclusively on these systems. Specifically, we have worked with aerovalve pulse combustors. These systems have been shown in prior work to support as great as 4 percent pressure increase (Kentfield and Fernandes 1990). The experimental research employed an atmospheric combustion rig as well as a pressurized combustion rig. Both systems have similar features, so only the atmospheric rig will be discussed here. A more detailed description of the pressurized rig has been reported (Gemmen et al. 1994). Figure 2 shows a typical configuration used for the atmospheric rig. Combustion air and fuel enter on the left at the inlet plenum. The combustion air enters directly into the inlet plenum, while the fuel is delivered to the combustor with typically a 1/8-inch diameter stainless steel tube. The combustion air and natural gas fuel mix inside the combustion chamber and ignite with the previous cycle’s exhaust products. (No ignition source is required except for start-up.) The exhaust products exit out of the combustor through a tailpipe and enter the dilution plenum where they mix with dilution air. From the dilution plenum, the gas passes out through an 8-meter exhaust duct to the atmosphere. Thermocouples are used for temperature measurement at several locations over the combustor for wall and gas temperatures. The dynamic pressure inside the combustor is measured using a Kistler model #206 transducer. For the atmospheric rig, mean pressure differences across the combustor (pressure gain) and from inlet plenum into the combustion chamber are measured using either a water manometer or a Setra model #226 low-differential pressure gage.

PRESSURE GAIN

The geometry that has produced the maximum pressure gain thus far in this work employs a flow rectification device taken after Kentfield and Fernandes (1990) and is shown in Figure 3. This geometry includes a by-pass tube that captures the reverse flow exiting out through the inlet. (Other geometries studied in our research that did not take advantage of the reverse flow energy showed poorer pressure-gain performance.) The by-pass tube included
Figure 2. Atmospheric Rig

Figure 3. Geometry With By-Pass Tube Producing 1 Percent Pressure Gain (After Kentfield and Fernandes 1990)
a ball valve to control the flow rate of fluid through the by-pass. The separation between the by-pass tube and the inlet to the combustor was adjustable with a tube that slid over the by-pass tube. Some results from the experiments using this (somewhat crude) mode of rectification are shown in Figure 4. From other tests, it was determined that nearly 1 percent could be achieved. For this later case, the total air flow through the combustor and by-pass was 23 g/s and the fuel flow rate was 1.1 g/s. Through the use of gas sample data, it was determined that 33 percent of the air was passing through the by-pass, which produced a time average equivalence ratio inside the combustion chamber of 0.44.

![Figure 4. Pressure Gain Versus Flow Rate for the Geometry Shown in Figure 3](image1)

**Figure 4. Pressure Gain Versus Flow Rate for the Geometry Shown in Figure 3**

**POLLUTANT EMISSIONS**

Not surprisingly, measurements of pollutant emissions depended strongly on combustor geometry. For geometries that did not use a by-pass tube, reasonable emissions of about 6 ppmv NOx and 50 ppmv CO could be expected for our atmospheric rig tests. (See Figures 5 and 6.) For the geometry shown in Figure 3, however, it was found that unburnt hydrocarbon (UHC) and CO emissions could be high in both tailpipe and by-pass flows -- about 175 ppmv and 1200 ppmv, respectively. NOx emissions were about 15 ppmv. Because the geometry of Figure 3 has not been optimized, these preliminary results should not be accepted as typical for this technology. Improvements discussed in the Future Work section explain the direction that needs to be taken.

**PRESSURE EFFECTS**

The effect of mean operating pressure on overall pressure gain can be determined by extending the work reported in Gemmen et al.
Figure 6. CO Versus Equivalence Ratio for a Combustor Operated at Atmospheric Pressure Without a By-Pass Tube (1994). In this work, single, non-rectified, combustor geometries were studied. There it was reported that the pressure gain achieved across the inlet to the combustor (normalized by operating pressure) increases slightly as operating pressure increased. (See Figure 7.) Such results can be predicted from the work of Narayanaswami and Richards (1994). They show that when the governing equations are suitably normalized, combustion operation (including pressure gain) is nearly insensitive to operating pressure. This result is especially true at high pressure where surface effects (friction and heat transfer) are of less significance.

Gemmen et al. (1994) prove that pollutant emissions for these highly unsteady combustion systems scale with pressure in the same manner as steady constant pressure combustion systems. In particular, NOx shows a $P^{0.28}$ effect and CO shows a $P^{1.17}$ effect. This is similar to the results reported by Rizk and Mongia (1993). Such results are beneficial for extending aerovlave pulse combustor results at low pressure to any other operating pressure.

WAVE ATTENUATION

As mentioned previously, all pressure-gain combustion systems necessarily require unsteady flow processes. It is important for purposes of reliability that any unsteadiness
caused by such combustion systems does not adversely affect the gas turbine system. Current steady flow gas turbine systems show about a 0.1 to 0.5 psi oscillation (Brandt and Wesorick 1994). To determine what might be expected for pressure-gain systems, the FLUENT computational fluid dynamics code was used for the problem shown in Figure 8. For this problem, FLUENT predicted the oscillation that could occur for a dual combustion system operating in-phase and anti-phase. It was shown that nearly a 90 percent reduction in pressure oscillation may be possible. Preliminary experimental data taken with two combustion systems operating anti-phase confirm that significant attenuation can be achieved. The magnitude of oscillation that remained downstream of the two combustors was about 0.024 psi for the atmospheric test. If scaled to 10 atmospheres, the expected oscillation amplitude would be about 0.24 psi. Hence, a negative impact to reliability can be avoided.

FUTURE WORK

Overall, we have been encouraged by the magnitude of pressure gain that these systems are capable of producing (1 percent gain versus 4 percent pressure loss in current designs). Such pressure-gain capability can be expected to produce a 1 percent boost in cycle efficiency compared to current systems. Based on our overall research program, we are confident that further increases in pressure gain are possible as well as reduced pollutant emissions. To achieve this performance, a dual combustion system such as that shown in Figure 9 is proposed. In this design, all fuel is converted inside a high-temperature flow path, thereby significantly reducing the pollutant formation produced by the by-pass design of Figure 3. In addition, since both flow paths experience a pressure boost, increased pressure gain above the design shown in Figure 3 can be expected. Furthermore, when operating anti-phase, minimal wave energy will exist outside the combustion system.

To further progress in this area, the Morgantown Energy Technology Center is looking for an industrial gas turbine partner to supply a low-pressure ratio turbine and to mutually investigate the actual benefits possible with this technology.

REFERENCES


Flow from Outlet Boundary Tailpipe

Dilution Flow

Flow from Tailpipe 1

0.14875 m

0.14875 m

Flow from Tailpipe 2

Adiabatic Walls

Operating Pressure: 10 atm
Dilution Flow: Steady, Velocity = 30 m/s, Temperature = 600K
Flow from Tailpipe 1: Velocity = 100 + 50sin (ωt + φ) m/s; Temperature = 1400 K
Flow from Tailpipe 2: Velocity = 100 + 50sin (ωt) m/s; Temperature = 1400 K
Tailpipe Height = 0.04 m
Grid: 202 cells x-direction x 30 cells y-direction

Figure 8. FLUENT Simulation of a Dual Combustor for Wave Attenuation
Figure 9. Example Dual Combustion System Proposed for Future Work to Achieve Maximum Pressure Gain and Reduced Pollutant Emissions


