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Authors:

Randall S. Gemmen (DOE/METC)
Michael C. Janus (DOE/METC)
George A. Richards (DOE/METC)
Thomas S. Norton (DOE/METC)
William A. Rogers (EG&G TSWV, Inc.)

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ACHIEVING IMPROVED CYCLE EFFICIENCY VIA PRESSURE GAIN COMBUSTORS

Randall S. Gemmen, Michael C. Janus,
George A. Richards, and Thomas S. Norton
U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia 26507-0880

William A. Rogers
EG&G Technical Services of West Virginia
Morgantown Energy Technology Center
Morgantown, West Virginia 26507-0880

ABSTRACT

As part of the Department of Energy's *Advanced Gas Turbine Systems Program*, an investigation is being performed to evaluate "pressure gain" combustion systems for gas turbine applications. This paper presents experimental pressure gain and pollutant emission data from such combustion systems. Numerical predictions for certain combustor geometries are also presented. We report that for suitable aerovalved pulse combustor geometries studied experimentally, an overall combustor pressure gain of nearly 1 percent can be achieved. We also show that for one combustion system operating under typical gas turbine conditions, NO_x and CO emissions, are about 30 ppmv and 8 ppmv, respectively.

1. INTRODUCTION

A pressure gain combustion system is one where the combustion process produces an end-state stagnation pressure that is greater than the initial-state stagnation pressure. The constant volume combustion event in an ideal spark-ignited engine is an example. Such constant volume combustion systems produce a greater available energy in the end-state gas than do constant pressure combustion systems. When applied to gas turbine cycles, it can be shown that under ideal conditions having a 10:1 pressure ratio and a 1200 K turbine inlet temperature, the efficiencies of a constant volume versus a constant pressure combustion system, are 54 percent and 48 percent, respectively, Gemmen, et al. (1994). Past investigations have attempted to apply this technology to gas turbines with varying degrees of success; Thring (1961), Muller (1971), Kentfield and O'Brien (1987a, 1987b), to name a few. While these investigations have indicated that it is possible to achieve pressure gain, no investigation has addressed the combined issues of pressure gain, pollutant reduction, and engine reliability. Given the significant potential for

improved cycle efficiency, investigators at the U.S. Department of Energy's Morgantown Energy Technology Center are evaluating the use of such devices as part of DOE's Advanced Turbine System program, Geiling (1993).

This paper presents results from five tasks in our initial evaluation of this technology:

- Evaluate the best combustor style for a *first-generation system* as well as pressure gain capability.
- Evaluate the pollutant emissions for combustors designed for pressure gain.
- Determine the effect of operating pressure on combustor performance.
- Determine the extent to which gas flow unsteadiness outside the combustor can be minimized to avoid excessive mechanical fatigue on turbine components.
- Determine other barrier issues that might preclude the use of pressure gain combustors in gas turbines.

2. PRESSURE GAIN COMBUSTION SYSTEMS

All practical pressure gain systems demand some form of unsteady fluid mechanics and combustion, Kentfield and O'Brien (1987a). One general category of combustion system, called pulse combustion, relies on the inherent unsteadiness of resonant chambers. Here, the periodic injection and consumption of air and fuel inside a combustion chamber sustains a resonant mode of fluid oscillation in an attached tube. Kentfield and Fernandes

(1990) show certain configurations of such devices to be capable of producing as much as 4 percent pressure boost.

Resonant combustion systems have three favorable characteristics that make them likely candidates for first-generation pressure gain systems. Since they are driven in a natural mode of instability, no mechanical mechanisms are required to produce the required unsteady fluid mechanics and combustion. Secondly, since their oscillations are nearly sinusoidal, it is possible for pairs of such systems to be run anti-phased so as to achieve wave attenuation. With the possibility of wave cancellation, the impact of fluid oscillations on gas turbine reliability can be minimized. Finally, certain styles of resonant systems (e.g., "aerovale" pulse combustors) are free of mechanically moving parts, such as "flapper valves" and "rotary valves," George and Corliss (1988). By avoiding mechanical components, detrimental impacts on gas turbine reliability, availability, and maintainability are avoided.

For these reasons, an aerovaled Helmholtz-type resonator has been solely used in our work. A simplified schematic is shown in Figure 1 along with a description of its operation.

3. EXPERIMENTAL CAPABILITIES

Both an atmospheric and pressurized experimental rig have been built to support this work. The atmospheric system allows fast evaluation of different geometries, while the pressurized system enables pressure effects to be understood -- an issue heretofore inadequately studied for gas turbine applications.

Figure 2 shows a schematic of the atmospheric rig. Combustion air enters on the left side of the containment pipe into the inlet plenum. Due to a separation plate that divides the inlet plenum from the dilution plenum, all the combustion air passes through the combustor. Fuel (either natural gas or propane) enters the combustion chamber on the upstream side near a step expansion. During operation, the fuel and combustion air mix inside the combustion chamber with the hot products from the previous cycle and are ignited, thereby reinforcing a resonant pressure wave. During the pressure decay portion of the combustion cycle, exhaust products exit out the tailpipe and mix with dilution air in the exhaust plenum. Also during the pressure decay, some of the combustion products may reverse out through the combustor inlet. To measure the oscillating combustion chamber pressure, a piezoelectric transducer is attached to a 6.4-mm diameter tube having a length of 152 mm and connected to the middle of the combustion chamber. For measuring mean pressure gain/loss across the combustor inlet, a water manometer can be connected between inlet plenum and combustion chamber. Due to the magnitude of the pressure oscillations, the side of the water manometer connected to the combustion chamber uses a 20-foot coil of copper tubing to help attenuate the pressure oscillations. For overall pressure gain/loss, one end of the water manometer is connected to the inlet plenum and the other is connected to the exhaust plenum.

A pressurized system, with largely the same general features as the atmospheric system, is shown in Figure 3. In this system, only natural gas fuel is used. Operating pressures can be

controlled from 1 to 11 atmospheres via a back pressure control valve. All flows can be scaled in the same proportion as the pressure. For this system, differential pressure gauge transducers are used for measuring both pressure gains/losses.

4. EXPERIMENTAL RESULTS ON PRESSURE GAIN

Single Combustors for Achieving Pressure Gain

Most of our initial experimental work was devoted to developing single-pulse combustors with pressure gain, without regard to wave attenuation. Figure 4 shows an initial configuration (containment pipe not shown) that was operated at near atmospheric pressure and produced modest overall gains of about 0.5 percent when operating at 7.5 g/s combustion air and 0.7 equivalence ratio. While a 0.5 percent gain is a significant improvement over the 3 to 4 percent losses typically cited for current steady combustion systems, other research suggests better performance can be achieved, Kentfield and Fernandes (1990).

In an attempt to take advantage of the inlet reverse-flow energy that may occur during the pressure decay portion of the cycle, another geometry similar to that of Kentfield and Fernandes (1990) was built and tested, Figure 5. Kentfield and Fernandes ran their combustor on propane. In our tests, both propane and natural gas were used, but only propane produced stable pressure-gain operation. As is shown, the reverse flow is captured by a 48-mm diameter tube and redirected downstream through the bypass duct. An adjustable length between the bypass duct and the combustor inlet was made possible with another tube that slid over the bypass tube inlet. For these tests, a ball valve was used to control the amount of fluid flowing through the bypass. Although this was a very crude attempt at flow rectification (no optimization was done on bypass tube diameter or bypass inlet or exit shape), significant overall pressure gain was achieved -- see Figure 6. It was determined from several other tests that for a suitable flow split through the bypass and combustor, a steady overall gain of nearly 1 percent could be achieved. For this case, the total air flow through the combustor and bypass was 23 g/s, and the fuel flow rate was 1.1 g/s. Through the use of gas sampling data, it was shown that for the 1 percent pressure gain case about 33 percent of the air was passing through the bypass producing an effective equivalence ratio in the combustor of about 0.44. While further work with this design will likely provide continued improvements in pressure gain, a new combustor design is being designed that enables a similar type of flow rectification, but with improved pollutant and wave attenuation characteristics (see Sections 5 and 6).

Effects of Pressure

Since very little fundamental research has been performed on pressurized pulse combustion systems, a study was performed to determine the effects of pressure on a simple geometry combustor without flow rectification, Gemmen, et al. (1994). Figure 7 shows the experimental combustor frequency and normalized

pressure oscillation as a function of vessel operating pressure. Also shown on the pressure graph are numerical predictions using a one-dimensional method of characteristics model, Janus (1993). Both the frequency and normalized pressure oscillation show only weak pressure dependence. The pressure effects become even weaker as pressure increases. The cause for this behavior can be attributed to both surface effects as well as chemistry, Gemmen, et al. (1994). Finally, it is seen that the numerical model reasonably predicts the pressure oscillations, although it shows a weaker pressure effect. This could be due to the combustion model employed that assumed a fixed temporal profile for the energy release in the combustion chamber.

Another test using the geometry presented in Figure 4 (which showed 0.5 percent gain at atmospheric pressure) was performed under pressurized conditions with all flows scaled in proportion to the pressure increase. At 11 atmospheres the combustor showed 0.43 percent pressure gain. It can be concluded that these combustors are largely unaffected by operating pressure provided all flows are scaled in proportion to the pressure increase. Such a behavior has also been predicted using control volume analyses, Narayanaswami and Richards (1994). They show that when the governing equations are suitably normalized, combustor operation is nearly insensitive to operating pressure, especially at high pressure where surface effects (friction/heat transfer) are relatively small, and chemical times have become short relative to mixing times. Consistent with thermodynamic analysis, the model also shows that inlet combustion air temperature can significantly modify the pressure gain performance of this style inlet. Higher inlet temperatures reduce the pressure gain performance. Such results are also evident in our experimental data. It is primarily for this reason that any constant volume combustion system performs best at low compressor ratios where the combustor inlet temperatures will remain low; for example, near 10:1 which is representative of industrial-scale gas turbines.

5. EXPERIMENTAL RESULTS ON POLLUTANTS

The fundamental mechanisms producing the relatively low NO_x in pulse combustors are gradually being understood, Keller and Hongo (1990). To assess emissions under pressure gain, several experiments have been performed with geometries similar to those discussed in Section 4. Figures 8 and 9 show pollutant emissions at *atmospheric pressure* for a straight inlet and tailpipe geometry (without flow rectification via a bypass duct). These figures indicate that optimum equivalence ratios for minimizing the sum of CO and NO_x are in the range of 0.7 to 0.8. It has been our experience, however, that for this geometry, equivalence ratios between 0.8 and 0.9 are required for achieving reasonable pressure gain. Even so, for this later range, less than 7 ppmv NO_x and 80 ppmv CO (at 15 percent oxygen) result. Since CO production is usually a wall effect, we anticipate that the CO level will reduce during scale-up and at higher pressure.

For the geometry with flow rectification shown in Figure 5, it was found that pollutant emissions could be very high in the tailpipe flow as well as in the bypass flow. Figure 10 shows the

total emissions for both flows as measured 2 m downstream of the tailpipe exit. NO_x emissions were as high as 15 ppmv, CO as high as 1300 ppmv, and UHC as high as 165 ppmv. For the case that produced best overall gain (~1 percent), nearly all the UHC were carried by the bypass flow, whereas most of the CO was carried by the tailpipe flow. It is felt that with continued work, however, the tailpipe emissions could be reduced to values similar to that of the non-rectified combustor. Even so, the emissions carried by the bypass flow may be difficult to eliminate, since little can be done once reactants ejected from the combustor mix with cool inlet plenum gases and become quenched. As discussed in Section 6, two combustors operating in tandem may improve the pollutant problem while still performing flow rectification.

Effects of Pressure

Figure 11 shows the effect of pressure on pollutant emissions for a straight inlet and tailpipe geometry (without any flow rectification), Gemmen, et al. (1994). In this study, the equivalence ratio was held constant at about 0.7 while pressure and flow rates were varied proportionally. At 10 atmospheres, Figure 11 shows NO_x and CO to be about 30 ppmv and 10 ppmv (at 15 percent O_2), respectively. These values, taken at conditions representative of industrial gas turbine, are comparable to currently marketed "dry-low- NO_x " systems, Farmer (1994). Thus, without optimization, this combustor design is competitive with current "low- NO_x " systems.

Figure 11 also shows that the effect of pressure is similar to typical steady flow combustors, Rizk and Mongia (1993). Specifically, for the available data, NO_x shows a $P^{0.28}$ effect and CO shows a $P^{-1.17}$ effect. It is concluded that for the conditions studied here, the large unsteady flows do not strongly modify the effect of pressure on pollutant formation. This result also reinforces the previously stated point that with the scaling of pressure and flows, the (normalized) pulse combustor operation is not strongly modified.

6. WAVE ATTENUATION

Before pressure gain technology can be considered viable for gas turbine applications, the effect of combustor oscillations on equipment reliability needs to be understood. Currently, gas turbine systems show pressure oscillations less than 0.5 psi for standard single-nozzle systems and less than 0.1 psi for multi-nozzle systems, Brandt and Wesorick (1994). To avoid added development costs, it is desirable that pulse combustion systems stay at or below these levels.

To assess the conditions downstream of the combustion systems presented here, the Fluent computational fluid dynamics computer code was used to predict the turbulent unsteady flow exiting the tailpipes of two combustors, see Figure 12. For simplicity, a two-dimensional cartesian simulation was performed. As an attempt to minimize setting up resonances within the computational domain (which are application specific), the results presented here were obtained by removing the gas compressibility

in the calculations. Given the relatively low Mach numbers (~ 0.2 and below), this may be a safe assumption. The input conditions selected for the simulation resemble typical industrial turbine inlet conditions: mean pressure of 1.0 MPa and mean flow temperature of about 1200 K. Both in-phase and anti-phase tailpipe simulations were performed. For both conditions, the mean mass flow through each tailpipe was the same as well as the oscillation amplitude.

Figure 12 shows the transient stagnation pressure along the centerline five tailpipe diameters downstream from the tailpipe exits. The benefits of employing anti-phased operation are significant. The unsteady stagnation pressure at this point has been attenuated by over 90 percent. Although obtained without pressure gain, preliminary experimental data of dual combustors at atmospheric pressure indicate pressure attenuation by at least 76 percent, which is close to that predicted by FLUENT. The magnitude of oscillation was 0.024 psi, which, based on results described in Sections 4 and 5 of this paper, indicates that at 10 atmospheres, the pressure amplitude would be approximately 0.24 psi. While both the numeric and experimental boundary conditions do not precisely represent those in the final gas turbine application, these preliminary results are encouraging.

7. FUTURE DIRECTION

Several more objectives need to be achieved before applying a pressure-gain combustor to a specific gas turbine: (1) improve pressure gain performance while maintaining pollutant emissions at levels comparable to steady-flow combustor alternatives; (2) minimize external flow oscillations; (3) assess the impact of increased combustor exit pressure on turbine blade cooling for gas turbines that extract compressor air for cooling the hot gas path; and (4) examine material and durability issues for combustor components.

In pursuit of the first two issues, Figure 13 shows a concept where both flow rectification (for improved pressure gain), as well as anti-phase operation (for minimal external pressure oscillations) are possible. Since the reverse inlet flow will not likely carry reactants to the inlet (due to the distance required), UHC and CO production via the reverse inlet flow will be non-existent. To address the effect of increased gas pressure exiting the combustor on turbine blade cooling, a closed loop steam cooling system may be required, Little, et al. (1993). Alternatively, another off-board compressor may be required to boost the cooling air pressure. Finally, if the above issues can be adequately addressed, material and durability issues will ultimately need to be investigated once a specific gas turbine is selected for development.

8. CONCLUSION

In his *R. Tom Sawyer Award Lecture*, Hawthorne (1994) challenged the gas turbine community to "*question conventional wisdom from time-to-time*" in the pursuit of improved turbine designs. Hawthorne specifically addressed the issue of modifying the thermodynamic cycle of gas turbines. The research reported

here, based considerably on the prior work of others (e.g., Kentfield (1988)), also examines the issue of cycle modification, and we have described specific designs that may be capable of providing a first-generation pressure gain combustor for gas turbines. In particular, the following observations have been made:

- Because of the need to avoid additional mechanical components and the need to achieve wave cancellation, aerovalve pulse combustors are strong candidates for first-generation pressure gain combustion systems.
- The effect of operating pressure on (normalized) combustor performance is weak provided all flows scale with pressure.
- Detailed numerical predictions show 90 percent wave attenuation outside the combustor which agrees approximately with preliminary experimental results showing pressure amplitudes near 0.25 psi when scaled to 10 atmospheres.
- Based on experimental tests, an overall gain of nearly 1 percent has been achieved via flow rectification.
- Under gas turbine conditions, NO_x and CO emissions are near 30 and 8 ppmv, respectively. In spite of the strongly oscillating flows, pollutants seem to scale with pressure in the same manner as steady flow combustors.
- Modifications to blade-cooling designs are needed when pressure gain systems are applied to gas turbine engines. Current advances in cooling (e.g., steam cooling and off-board air compression) may provide the necessary options to make the pressure gain technology feasible.

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Principles Of Operation

FIGURE 1. OPERATION OF A HELMHOLTZ-TYPE PULSE COMBUSTOR. THE COMBUSTION EVENT RAISES PRESSURE IN THE COMBUSTION CHAMBER FORCING GASES OUT THE INLET PIPE AND TAILPIPE. MOMENTUM OF THE FLUID IN TAILPIPE FORCES NEW GAS IN THROUGH THE INLET AND A COMPRESSION OF THE GASES IN THE COMBUSTION CHAMBER. ON A TIME AVERAGE, FLOW MOVES FROM LEFT TO RIGHT.

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Atmospheric Pressure Aerovalve Pulse Combustor Assembly

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FIGURE 2. SCHEMATIC OF THE ATMOSPHERIC EXPERIMENTAL RIG.

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FIGURE 3. SCHEMATIC OF THE PRESSURIZED EXPERIMENTAL RIG.

FIGURE 4. CONFIGURATION THAT PRODUCED OVERALL PRESSURE GAINS OF ABOUT 0.5 PERCENT RELATIVE TO MEAN INLET CONDITIONS.

FIGURE 5. CONFIGURATION BASED ON KENTFIELD AND FERNANDES (1990) WITH MODIFIED BYPASS LINE.

FIGURE 6. EXPERIMENTAL COMBUSTOR PRESSURE GAIN VS. FLOW RATE FOR CONFIGURATION SHOWN IN FIGURE 5.

FIGURE 7. EXPERIMENTAL COMBUSTOR FREQUENCY AND NORMALIZED PRESSURE OSCILLATION AS A FUNCTION OF VESSEL OPERATING PRESSURE FOR A COMBUSTOR WITH A 24-MM DIAMETER BY 151 MM LONG INLET, 19 MM DIAMETER BY 460 MM LONG TAILPIPE WITH A 26.6-MM DIAMETER BY 102 MM LONG EXTENSION, AND 56 MM DIAMETER BY 152 MM LONG COMBUSTOR.

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FIGURE 8. NO_x EMISSIONS AT ATMOSPHERIC CONDITIONS FOR A STRAIGHT INLET AND TAILPIPE GEOMETRY.

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FIGURE 9. CO EMISSIONS AT ATMOSPHERIC CONDITIONS FOR A STRAIGHT INLET AND TAILPIPE GEOMETRY.

FIGURE 10. TOTAL EXHAUST EMISSIONS RESULTING FROM BOTH BYPASS AND TAILPIPE FLOWS FOR THE GEOMETRY SHOWN IN FIGURE 5.

FIGURE 11. EFFECT OF PRESSURE ON POLLUTANT EMISSIONS FOR A STRAIGHT INLET AND TAILPIPE GEOMETRY (WITHOUT FLOW RECTIFICATION VIA A BYPASS DUCT).

Operating Pressure: 10 atm

Dilution Flow: Steady, Velocity = 30 m/s, Temperature = 600K

Flow from Tailpipe 1: Velocity = $100 + 50\sin(\omega t + \phi)$ m/s; Temperature = 1400K

Flow from Tailpipe 2: Velocity = $100 + 50\sin(\omega t)$ m/s; Temperature = 1400K

Tailpipe Height = 0.04 m

Grid: 202 cells x-direction x 30 cells y-direction

FIGURE 12. FLUENT SIMULATION RESULTS OF TWO UNSTEADY TAILPIPE EXHAUST FLOWS (IN-PHASE AND ANTI-PHASE) MIXING TOGETHER. RESULTS SHOW THE STAGNATION PRESSURE OSCILLATION AT A DISTANCE FIVE TAILPIPE DIAMETERS DOWNSTREAM FROM THE TAILPIPE EXITS.

FIGURE 13. CONCEPT WHERE BOTH FLOW RECTIFICATION (FOR IMPROVED PRESSURE GAIN), AS WELL AS ANTI-PHASE OPERATION (FOR MINIMAL EXTERNAL PRESSURE OSCILLATIONS) ARE POSSIBLE.