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ULTRA-LOW NO_X ADVANCED VORTEX COMBUSTOR

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ABSTRACT

An ultra lean-premixed Advanced Vortex Combustor (AVC) has been developed and tested. The natural gas fueled AVC was tested at the U.S. Department of Energy's National Energy Technology Laboratory (USDOE NETL) test facility in Morgantown (WV). All testing was performed at elevated pressures and inlet temperatures and at lean fuel-air ratios representative of industrial gas turbines. The improved AVC design exhibited simultaneous NO_x/CO/UHC emissions of 4/4/0 ppmv (all emissions are at 15% O_2 dry). The design also achieved less than 3 ppmv NO_x with combustion efficiencies in excess of 99.5%. The design demonstrated tremendous acoustic dynamic stability over a wide range of operating conditions which potentially makes this approach significantly more attractive than other lean premixed combustion approaches. In addition, a pressure drop of 1.75% was measured which is significantly lower than conventional gas turbine combustors. Potentially, this lower pressure drop characteristic of the AVC concept translates into overall gas turbine cycle efficiency improvements of up to one full percentage point. The relatively high velocities and low pressure drops achievable with this technology make the AVC approach an attractive alternative for syngas fuel applications.

INTRODUCTION

The AVC concept is fundamentally different from conventional swirl-stabilized combustors since the flame stabilization mechanism is completely different. The swirling flow of a conventional gas turbine combustor produces a reverse flow along the axis—or core—of the main flow [1]. This back-mixing of hot products ignites the incoming fuel-air mixture and sustains continuous combustion. It is believed that this method of flame stabilization is more susceptible to process upsets and instabilities. Although swirl-stabilized combustors have been used for decades, achieving less than 3 ppmv NO_x emissions is complicated by the sensitivity to instabilities and sudden flame extinction near the lean blow-off limit [2-4].

In contrast, the AVC flame stabilization is accomplished by a stable vortex that is produced adjacent to the main fuel-air flow path. The vortex behavior is virtually independent of the main flow characteristics which make this method of flame stabilization so attractive. In order to work properly, the AVC concept must provide flame stabilization by lateral mixing from the vortex region into the main flow.

In an AVC concept the re-circulation of hot products into the main fuel-air mixture is accomplished by incorporating two critical features. First, a stable recirculation zone must be generated adjacent to the main fuel-air flow. If the vortex region, or cavity region, is designed properly, the vortex will be stable and no vortex shedding will occur. This stable vortex is generally used as a source of heat, or hot products of combustion.

The second critical design feature involves transporting and mixing the heat from the vortex, or cavity, region into the main flow. As described in previous work [5,6], this is generally accomplished by using wake regions generated by bodies, or struts, immersed in the main flow. This approach ignites the incoming fuel-air mixture by lateral mixing, instead of a back-mixing process. By using geometric features to ignite the incoming fuel-air mixture, instead of pure aerodynamic features, the AVC concept has the potential to be less sensitive

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◆ Corresponding Author: rsteele@ramgen.com to instabilities and process upsets. This is particularly important near the lean flame extinction limit, where small perturbations in the flow can lead to flame extinction.

In an effort prior to this project, Ramgen Power Systems (RPS) utilized an AVC concept to achieve 9 ppmv NO_x and 9 ppmv CO emissions on a lean premixed AVC [7]. In an independent effort, the USDOE NETL investigated a non-premixed rich-quench-lean version of the AVC concept to investigate the ability to achieve low emissions [8,9] and reduce conversion of fuel-bound nitrogen to oxides of nitrogen. Therefore, both organizations have significant operating and test experience with the AVC concept, but achieving NO_x levels of less than 3 ppmv at realistic gas turbine operating conditions was a challenging goal.

This paper presents the results of the second phase of AVC concept development and testing at typical industrial gas turbine operating conditions. The combustor is nominally 1 MW_t. It was designed as a research burner and is not engine specific. The project was a joint effort between RPS and the USDOE NETL with support from the California Energy Commission's Public Interest Energy Research Program. The improved AVC concept was tested and evaluated for emissions, flame stability, through-put velocities, pressure acoustic oscillations, and overall pressure drop. The emphasis of these tests was to reduce the NO_x emissions within the primary region of the AVC combustor and not to optimize the overall combustor design for reduction of CO to CO_2.

NOMENCLATURE

ppmv	*parts per million by volume corrected to 15% oxygen dry*
EI_i	*Emissions index for species i,* g_i/kg_{fuel}
Φ_{main}	*Main equivalence ratio based on main premixed fuel and air flow, excludes cavity fuel and air flows*
Φ_{cav}	*Cavity fuel-air equivalence ratio, only considering the fuel and air injected directly into the vortex cavity*
Φ_{total}	*Total fuel-air equivalence ratio, considering all the fuel and air injected into the combustor, includes the combustor cooling air*
η_{comb}	*Combustion efficiency*
RPS	*Ramgen Power Systems*
NETL	*National Energy Technology Laboratory*
AVC	*Advanced Vortex Combustor*

TEST FACILITY AND HARDWARE

The AVC hardware tested in this development program was very similar in form to that shown in Bucher [7] (See Figure 1). The cavity arrangement has not been changed significantly, and the main combustor section is also air cooled with some improvements and increased modularity. Downstream of the main combustor is a 14.0 cm (5.5-inch) inner diameter water cooled section for greater CO burnout.

Testing of the AVC was conducted in the USDOE NETL Low Emission Combustion Test and Research facility. The nominal test conditions are shown in Table 1. Airflow was split into main air, cavity air, and cooling air similar to the combustor described in Bucher [7]. The fuel used in this study was natural gas supplied by the local gas company. Although the composition of the natural gas was not a variable in this experiment, a fuel sample was taken daily and analyzed with average composition as shown in Table 2.

Table 1: Design Point Operating Conditions

Combustor Pressure [atm (psia)]	10 (147)
Inlet Preheat Temperature [K (°F)])	603 (625)
Total Air Flow Rate [kg/s (lb/s)]	0.73 (1.62)

Table 2: Average Natural Gas Composition

Analysis	***Average Test Day Values (Vol. %)***
CH4	89.9
C2H6	7.3
C3H8	1.0
C4 +	0.6
N2 + trace species	1.2
Average MW	17.8

The existing test rig was fabricated using 24-inch pipe sections and flanges. The assembled test rig is shown in Figure 2. The combustor components were assembled outside the vessel and lifted into position for testing. The pressure vessel has four 17.8 x 30.4 cm (7 x 12-inch) optical access ports. Optical access was also designed into the AVC for visualization of flow in the cavity region. This is the same test section that was used in the USDOE Simulation and Validation Studies Project [10,11].

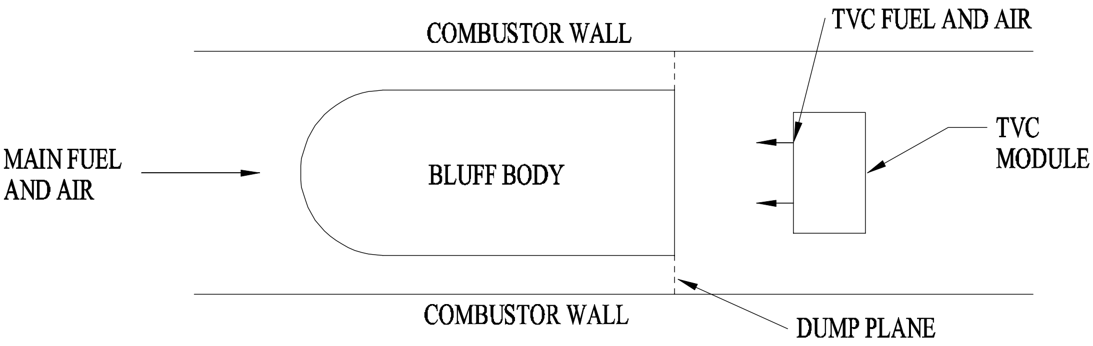

Figure 1: AVC Hardware Layout

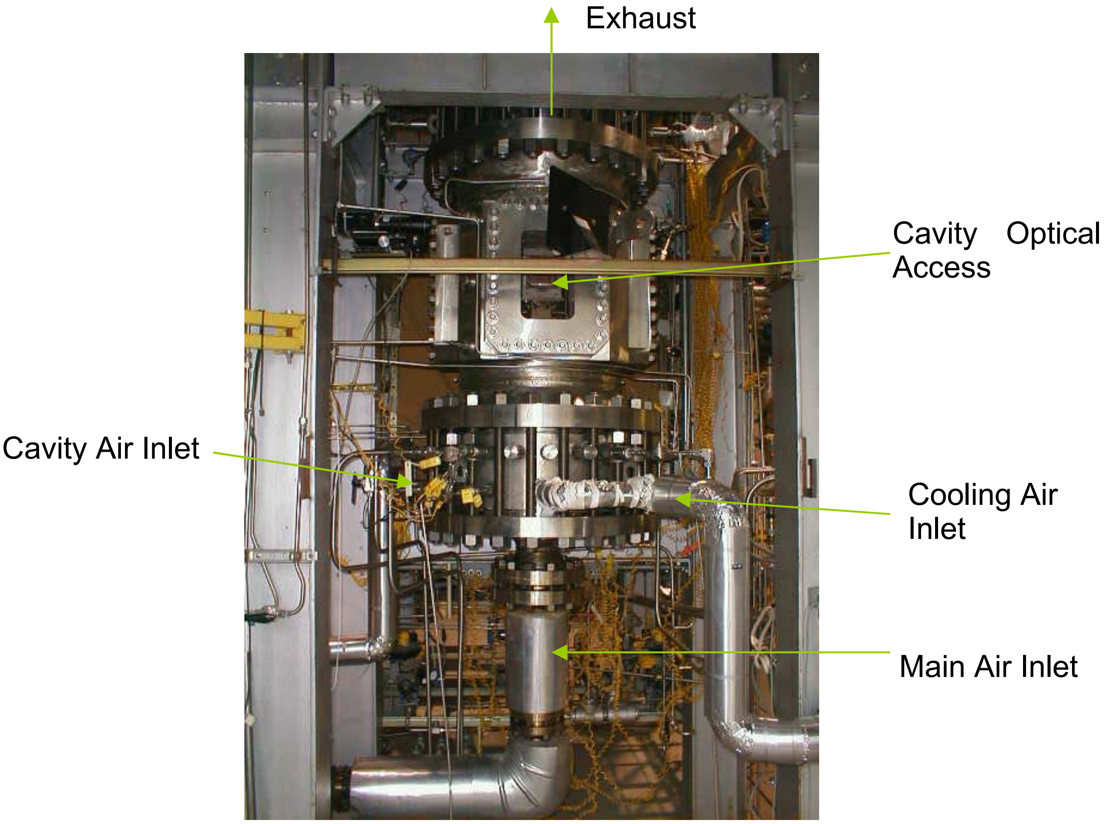

Figure 2: Photo of NETL test section with AVC installed

The exhaust gas sample system was updated for measuring 3 ppmv NO_x emissions. The exhaust gas sample was collected through a water-cooled area-weighted sample probe located at the exit of the combustor. The positive pressure gas sample measurements included UHC, O_2, NO_x, CO, CO_2.

Condensation in the sample system is particularly important to avoid when making single-digit NO_x measurements due to the solubility of NO_2 in water. Any NO_2 dissolved in the condensate that is removed from the sample will bias the NO_x measurements. To prevent this, the sample line was electrically heated to prevent condensation of water vapor upstream of the chiller/dryer.

A schematic flow diagram for the gas sampling system is shown in Figure 3. A small pressure control valve was used to vent excess flow though the sampling system and maintain a constant pressure in the gas analyzer manifold. The pressure control valve was finely tuned and closely monitored during testing due to the sensitivity of several analyzers to slight changes in flow or pressure. There were also a series of block valves that allowed the chiller and gas analyzers to be isolated while high pressure nitrogen was used to back-flush the sampling system.

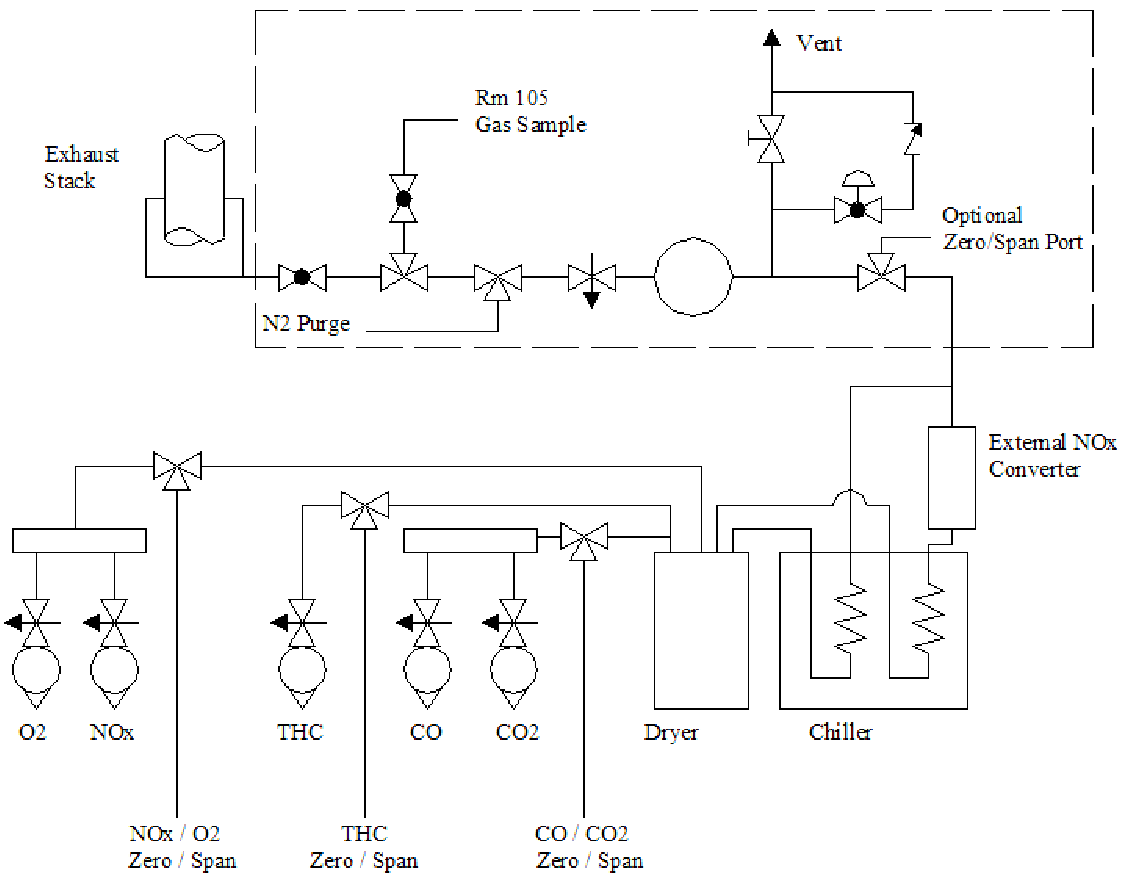

Figure 3: Process flow schematic for the gas

In order to prevent loss of NO_2 in the chiller/dryer unit, a NO_2-to-NO converter was installed immediately upstream of the chiller/dryer. This device uses a heated catalyst bed to convert NO_2 to NO. Since NO has extremely low solubility in water, this converter minimized the potential of NO_2 coming in contact with condensate in the chiller/dryer unit. The conversion efficiency for this converter was determined to be 90 to 95 percent. The dryer unit uses a peristaltic pump to continuously remove condensate as it forms. By continuously removing the condensate, the loss of NO_2 due to gas-liquid contact with condensate was further reduced.

The NO_x measurements were taken with a Horiba model CLA-510 SS. The analyzer was run in its lowest measurement range of 0-20 ppmv where it has a manufacturer specified accuracy of ± 0.2 ppmv. The CO analyzer used was an API Gas Filtration Model 300. All of the gas analyzers were calibrated daily during testing. Each analyzer was checked with a zero gas and a span gas. Although not shown in Figure 3, a Thermo ONIX (Model Prima delta-B) mass spectrometer was also used to measure certain key gas components, like CO_2 and O_2. This redundancy allows a secondary check of the O_2 and CO_2 readings during operation.

EXPERIMENTAL RESULTS AND ANALYSIS

As previously noted, the manufacturer specified instrument accuracy for the NO_x analyzer is ± 0.2 ppmv. In actual practice there are several other factors that affect the measurement error, such as process and flow variations. A specific operating point was replicated several times in an attempt to estimate the error in the gas analysis measurements. These replications were collected in a randomized order to achieve an improved estimate of the error. Using this approach, the NO_x analyzer had an uncertainty (95% confidence) of $\pm$ 1.2 ppmv. An underlying assumption was that the uncertainty was representative of the remainder of the experimental domain.

The combustor variables investigated included:

- Liner cooling air pressure drop, DP
- Cavity equivalence ratio, Φ_{cav}
- Main equivalence ratio, Φ_{main}
- Premixer reference velocity.

Cooling air pressure drop and cavity equivalence ratio were found to have the greatest effects on the combustor performance. A decrease in cooling flow changed the cavity and main combustor equivalence ratio due to mixing of the cooling air flow. The cooling air pressure drop and the premixer reference velocity are related when the pressure drop over the liner approaches the combustor pressure drop. When this occurs, further changes in the premixer reference velocity will reduce the liner pressure drop. The results of these test variables are presented below.

Cooling Air Effects

The cooling air pressure drop, and subsequently the cooling air flow rate, had a dramatic effect on the CO emissions and the overall combustor performance (see Figure 4). The cavity air loading is held constant for the data shown in this section. The cavity air loading is defined as the fraction of air injected into the cavity region relative to the sum of the cavity and main air flow. The reference velocity through the main premixer is maintained at 72 m/s (235 feet per second), and the cavity equivalence ratio is held constant. Figure 4 shows that the CO emissions were reduced significantly and the point at which the CO began to increase suddenly shifted to a lower main equivalence ratio as a result of decreasing the pressure drop from 3.5% to 2%. This dramatically increased the operating range for the combustor.

Figure 5 shows that the NO_x emissions increase for the same Φ_{main} as the cooling air pressure drop is decreased. This result was expected since some of the liner cooling air mixes with the cavity reactants. Decreasing the cooling air flow increases the cavity region fuel-air ratio. However, a lower main equivalence ratio can be reached allowing for further decreases in the NO_x emissions. Further analysis of the 2% combustor liner DP CO data revealed that the CO does not change significantly when plotted as a function of the total equivalence ratio which includes the effect of the cooling air flow rate. In summary, the total equivalence ratio of the combustor does not significantly change due to these changes in cooling air pressure drop. The primary advantage gained by operating at a lower liner pressure drop is an increase in the cavity equivalence ratio due to decrease cooling air dilution and lower CO emissions.

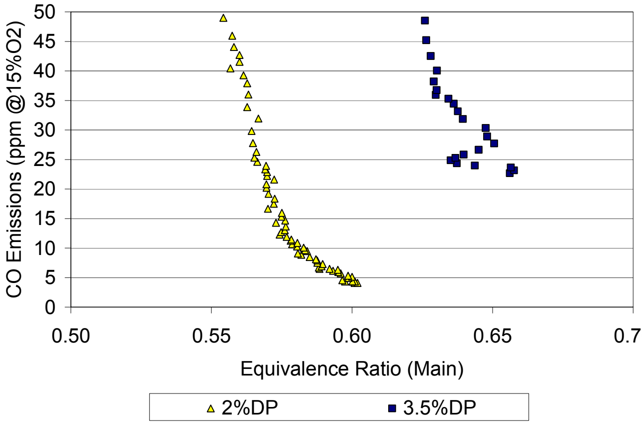

Figure 4: Effect of cooling air pressure drop on CO emissions

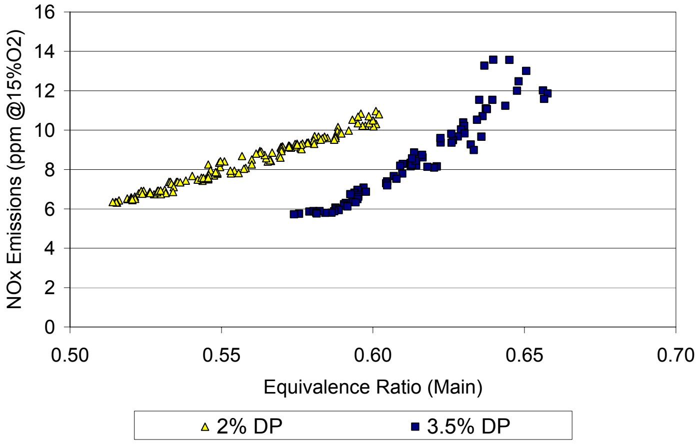

Figure 5: Effect of cooling air pressure drop on NO_x emissions

Cavity Equivalence Ratio Effects

The cavity equivalence ratio was varied in order to reduce the NO_x emissions and shift the CO-NO_x data to lower combined emissions. These tests were conducted using 2% liner pressure drop which allowed for further reductions in Φ_{cav}. Note that the cavity equivalence ratio represents the fuel-air ratio of the jets entering the cavity region. These values do not include the local effects of the cooling air, therefore, the actual equivalence ratio in the cavity is lower.

Figure 6 shows the NO_x levels for the baseline cavity equivalence ratio (i.e, Fuel Setting 1) and the NO_x levels for lower cavity equivalence ratio conditions. For each data set shown in Figure 6, the main fuel flow was varied while all other flows and the cooling air pressure drop were kept constant. The different fuel settings represent different levels of fuel flow for the cavity. The NO_x reduction from the baseline condition is approximately 3 ppmv, or in excess of 50 percent. At a main equivalence ratio of 0.54, the NO_x emissions are below the program goal of 3 ppmv.

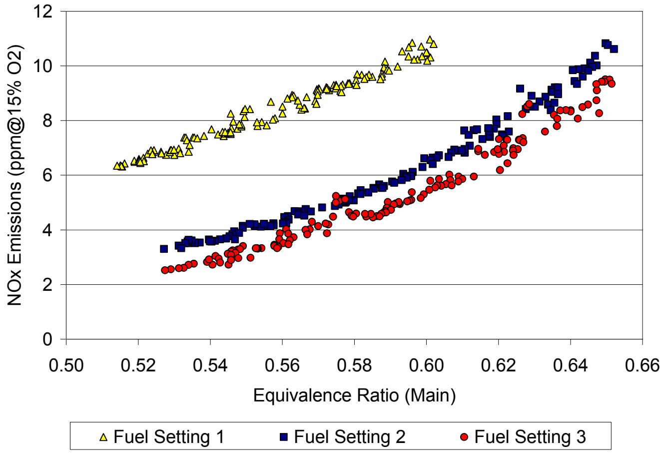

Figure 6: Effect of cavity equivalence ratio on NO_x emissions, Note: Fuel Setting 3 is leanest cavity operating condition.

Further reductions in the cavity equivalence ratio resulted in flame extinction at these operating conditions. It was concluded that these emission levels were optimized for this operating condition and combustor geometry. However, with some modifications to the combustor configuration, it will be possible to further reduce the cavity equivalence ratio in order to achieve even better performance.

The CO-NO$_x$ data are shown in Figure 7. This figure shows that the curve has shifted to lower NO$_x$ levels for different fuel settings. Furthermore, since each curve shifts to the left but does not shift upward, it is observed that the CO emissions are insensitive to cavity equivalence ratio. Each curve has the same general form, but moves to decreasing NO$_x$ values with decreasing cavity equivalence ratio.

The emphasis of these tests was to reduce the NO$_x$ emissions within the primary region of the AVC combustor and not to optimize the overall combustor design for reduction of CO to CO$_2$. The reduction of CO emission is dependent on the post flame zone of the combustion process, which is directly related to the design and shape of the combustor. The full optimization of a complete AVC system will be the priority of the next test program.

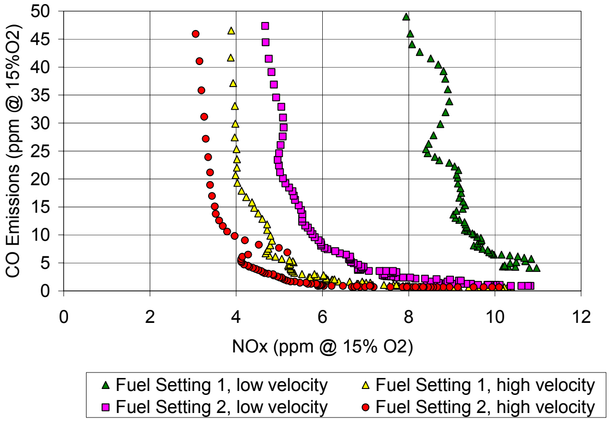

Figure 7: Effect of cavity equivalence ratio on CO- NO$_x$ curve, Note: Fuel Setting 2 is leanest cavity operating point for both velocity conditions.

Premixer Reference Velocity Effect

Although the initial results suggested that the reference velocity had no effect on the observed NO$_x$ and CO emissions, some experience from the exploratory screening tests suggested that lower cavity equivalence ratio conditions could be achieved at a higher bulk reference velocity through the premixer. At higher reference velocity, the CO-NO$_x$ curve is shifted further to the left (see Figure 7). This test showed that the point at which the CO began to increase suddenly (i.e., the "knee" of the curve) shifted to a lower main equivalence ratio. It should be noted that increasing the bulk velocity is similar to reducing the cooling air pressure drop, as discussed previously.

The same data showed no variation in the CO-NO$_x$ curve when compared using the total equivalence ratio, Φ_{total}. This behavior suggests that increasing the reference velocity through the premixer reduced the relative effect of the cooling air. Therefore, the total equivalence ratio shifted to higher values by increasing the reference velocity which should produce higher flame temperatures that are favorable for CO oxidation.

Combustion Efficiency

In order to be consistent with the previous results [7] and evaluate the completeness of the combustion, the combustion efficiency was calculated based on a heat basis using the following equation [12]:

$$\eta_c = 100\left[1 - 10109\frac{EI_{CO}}{LHV} - \frac{EI_{UHC}}{1000}\right]$$

The terms EI$_{CO}$ and EI$_{UHC}$ represent the CO and unburned hydrocarbon emissions expressed in terms of grams-per-kilogram of fuel. Furthermore, the lower heating value of the fuel is expressed as LHV (J/kg) in the previous expression. The second term in brackets represents the energy lost in forming CO instead of CO$_2$, and the last term in brackets represents the energy lost by unburned fuel.

For the high velocity data shown in Figure 7, the combustion efficiency is calculated and plotted as a function of the NO$_x$ emissions (see Figure 8). The combustion efficiency is 99.5 percent at the NO$_x$ level of 2.5 ppmv. However, for the steep portion of the curve shown in Figure 8, the uncertainties in combustion efficiency can be significant due to the rapidly changing CO and unburned hydrocarbon emissions in this region.

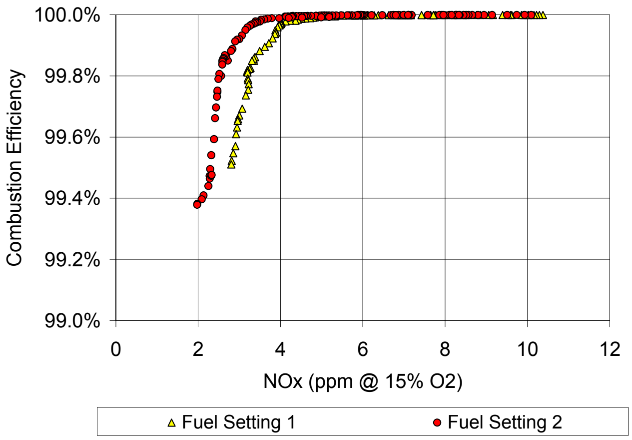

Figure 8: Combustion efficiency at highest bulk velocity, Note: Fuel Setting 2 is leanest cavity operating condition.

Dynamic Stability

One of the significant technical challenges for low emission gas turbine combustors, particularly those that utilize lean premixed technology, is controlling combustion driven oscillations. Combustion instabilities occur when fluctuations in the heat-release rate couple with the acoustics of the combustion system to produce pressure oscillations

Combustion driven oscillations were evaluated for this AVC configuration. Two high speed pressure transducers (Kistler Model #206) were located in the premixer region of the combustor to detect pressure oscillations. Due to temperature limitations, these sensors were located outside the pressure vessel on an infinite coil, which is the typical approach used in combustor test rigs. The signal from these pressure transducers was collected on a digital tape recorder (TEAC Model RD-135) at sampling rates of 24,000 samples per second. The output from one of these transducers was also analyzed using a Root Mean Square (RMS) meter, and the output from this RMS meter was stored in data acquisition system.

The CO emission (primary y-axis) and the RMS pressure (secondary y-axis) as a function of NO_x emissions are shown in Figure 9 for two main equivalence ratio sweeps. Note that the data shown in Figure 9 corresponds to the high premixer reference velocity data shown in Figure 7. The RMS pressure values remain very low with increasing CO and about an order of magnitude less than the typically accepted industrial level of 1.5% RMS. These RMS pressure levels are representative of the levels observed for all of the testing. In summary, no significant pressure oscillations were observed during the testing of the AVC. Although not an original design goal, the dynamic stability of this design is arguably the most significant achievement of this project.

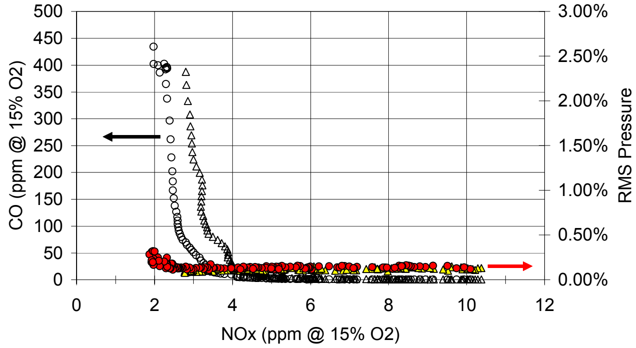

Figure 9: CO and RMS Pressure as a function of NO_x
Note: Colored data is RMS pressure;
black and white data is CO.

Combustor Pressure Drop

One of the advantages of the AVC approach over a swirl-stabilized combustor is the fact that no swirl vanes are required. The process of generating swirl in the main air flow requires energy that ultimately becomes an efficiency penalty for conventional gas turbines. Conventional gas turbine combustor pressure drops are typically 4% to 5% at nominal premixer velocities of 150 to 200 feet per second. The data collected during these tests indicated that the AVC concept is capable of achieving significantly lower pressure drop operation at even higher velocities than a conventional swirl-stabilized combustor (see Figure 10).

Preliminary calculations suggest a potential increase in overall gas turbine efficiency of up to one full percentage point is attainable with incorporation of the AVC concept. The lower pressure drop of the AVC is an attractive feature, not only for gas turbine applications, but also for other applications, such as industrial burners.

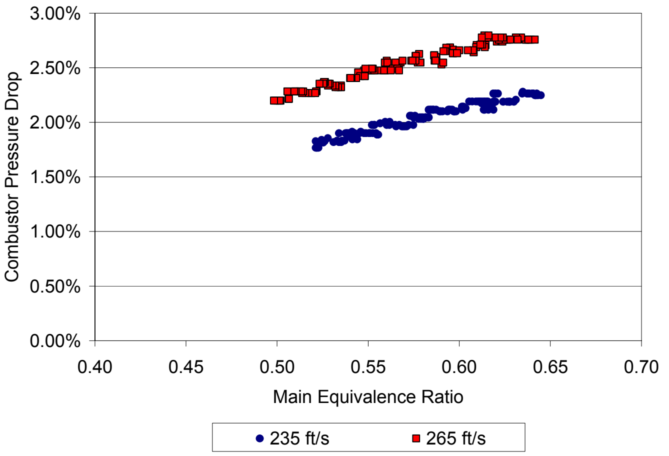

Figure 10: Combustor pressure drop measurements at two reference velocity conditions

Emissions data taken from Phase 1 and Phase 2 of the AVC development programs are presented in Figure 11. The lowest combination of CO and NO_x emissions shifted from 10 and 10 ppmv for Phase 1 to 4 and 4 ppmv for Phase 2. The scatter in the NO_x data at 4 ppmv is a result of an irregularity in the sample system however this variation of 1 ppmv is within the 95% confidence interval for these NO_x measurements. Figure 11 also shows a decrease in NO_x emissions from 6 ppmv to 3 ppmv at a measured CO emission of 45 ppmv.

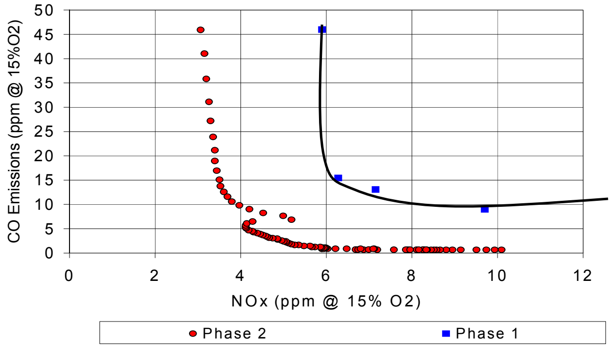

Figure 11: Comparison of Emissions from Phase1 and 2

CONCLUSIONS

The results show that the AVC approach is capable of achieving less than 3 ppmv NO_x levels at combustion efficiencies in excess of 99.5 %. These results have been obtained at realistic industrial gas turbine operating conditions.

The combustor pressure drop is significantly lower than conventional swirl-stabilized combustors. The AVC combustor pressure drop varied from a minimum of 1.75% at 72 m/s (235 feet-per-second) bulk premixer velocity to a maximum of 2.8% at 81 m/s (265 feet-per-second). Therefore, the lower pressure drop characteristics of the AVC concept will translate into efficiency improvements in an overall gas turbine cycle.

The impingement/effusion air cooling design used in this effort has been very effective at maintaining liner temperatures below the design limit. In fact, the amount of cooling air has a dramatic effect on the emissions performance. As the cooling air pressure drop is reduced from 3.5% to 2%, the measured CO emissions drop by more than an order of magnitude. With a lower cooling air pressure drop, the combustor can operate at leaner conditions. The wider operating range allows lower NO_x emissions to be achieved.

The cavity equivalence ratio has a profound effect on the emissions performance of this AVC design. A 15% reduction in the cavity equivalence ratio reduces the NO_x emissions by approximately 50% (or about 3ppmv), without a significant change in the CO emissions. Further reductions in NO_x emissions may be possible by using an approach that reduces the cavity equivalence ratio further without causing flame extinction.

The most noteworthy aspect of the testing was the lack of significant combustion oscillations. A full understanding of this observation will potentially lead to improvements of industrial gas turbine combustor designs.

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REFERENCES

[1] Sturgess, G.J., Shouse, D., "Lean Blowout Research in a Generic Gas Turbine Combustor with High Optical Access," Proceedings of ASME Turbo Expo 1993, Paper 93-GT-332.

[2] Steele, R.C., Cowell, L.H., Cannon, S.M., Smith, C.E., 2000, "Passive Control of Combustion Instability in Lean Premixed Combustors," Journal of Engineering for Gas Turbines and Power, **122**, pp. 412-419.

[3] Richards, G.A., Janus, M.C., "Characterization of Oscillations During Premix Gas Turbine Combustion," Proceedings of ASME Turbo Expo 1997, Paper 97-GT-244.

[4] Lieuwen, T., Zinn, B.T., "Theoretical Investigation of Combustion Instability Mechanisms in Lean Premixed Gas Turbines," 1998, Presented at the 36th Aerospace Sciences Meeting & Exhibit, AIAA paper 98-0641.

[5] Hsu, K.Y., Goss, L.P., Roquemore, W.M., 1998, "Characteristics of a Trapped Vortex Combustor," Journal of Propulsion and Power,**14** (1) pp. 57-65.

[6] Roquemore, W.M., Shouse, D., Burrus, D, Johnson, A., Cooper, C., Duncan, B., Hsu, K.-Y., Katta, V.R., Sturgess, G.J., and Vihinen, I., 2001, "Trapped Vortex Combustor Concept for Gas Turbine Engines," AIAA paper 2001-0483.

[7] Bucher, J., Edmonds, R. G., Steele, R. C., Kendrick, D., Chenevert, B., Malte, P., "The Development of a Lean Premixed Trapped Vortex Combustor," Proceedings of ASME Turbo Expo 2003, ASME Paper GT2003-38236.

[8] Straub, D. L., Sidwell, T.G., Maloney, D.J., Casleton, K.H., Richards, G.A., Rogers, W.A. and Golden, G.M., 2000, "Simulations of a Rich Quench Lean (RQL) Trapped Vortex Combustor," American Flame Research Committee (AFRC) International Symposium, Newport Beach, CA.

[9] Straub, D. L., Casleton, K. H., Lewis, R. E., Sidwell, T. G., Maloney, D. J., and Richards, G. A., 2005, "Assessment of RQL Trapped Vortex Combustor For Stationary Gas Turbines," Journal of Engineering for Gas Turbines and Power, **127**(1), pp. 36-41.

[10] Sidwell, T., Casleton, K., Straub, D., Maloney, D., Richards, G., Strakey, P., Ferguson, D., and Beer, S., 2005, "Development and Operation of a Pressurized Optically-Accessible Research Combustor for Simulation Validation and Fuel Variability Studies", Proceedings of ASME Turbo Expo 2005, Paper GT2005-68752.

[11] Sidwell, T., Richards, G., Casleton, K., Straub, D., Maloney, D., Strakey, P., Ferguson, D., Beer, S., and Woodruff, S., 2004, "SimVal: An Optically Accessible Pressurized Research Combustor for CFD Model Validation", Submitted for publication in AIAA Journal of Propulsion and Power Special Section on "Combustion Modeling and LES: Development and Validation Needs for Gas Turbine Combustors", Paper J15197.

[12] SAE Report ARP #1533 1982, "Procedure for the Calculations of Basic Emission Parameters for Aircraft Turbine Engines," Society of Automotive Engineers, Warrendale, PA.