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THE DEVELOPMENT OF A LEAN-PREMIXED TRAPPED VORTEX COMBUSTOR

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ABSTRACT

A lean-premixed trapped vortex combustor (TVC) has been developed and tested. The TVC was fired on methane and tested at the General Applied Sciences Laboratory (GASL). Additionally, for baseline data, a simple bluff body combustor was tested. All testing was performed at elevated pressures and inlet temperatures and at lean fuel-air ratios representative of power generation gas turbine engines. Both bluff body and TVC data showed competitive oxides of nitrogen (NOx) emissions of <25 ppm (corrected to 15% oxygen dry condition), which served as a basis for future optimization. Combustion efficiency was routinely above 99.5%. An optimized version of the TVC incorporating flame stabilizing features displayed promising emissions: NOx/CO/UHC levels were optimized to as low as 9/9/0ppm (corrected to 15% O2 dry), with corresponding combustion efficiency above 99.9%. Because of this configuration's robust and straightforward design, it has the potential for successful integration into a prototype engine. This paper describes the combustors, their testing and the evaluation of the test results.

INTRODUCTION

Combustion stability is often achieved though the use of recirculation zones to provide a continuous ignition source which facilitates the mixing of hot combustion products with the incoming fuel and air mixture (Zukoski and Marble, 1955, Kendrick, 1995). Swirl vanes, bluff bodies and rearward facing steps are commonly employed to establish recirculation zones for flame stability. Each method creates a low velocity zone of sufficient residence time and turbulence levels such that the combustion process becomes self-sustaining. The challenge, however, is selection of a flame stabilizer which ensures both performance (emissions, combustor acoustic and pattern factor) and cost goals are met.

As opposed to conventional combustion systems which rely on swirl stabilization, the TVC employs cavities to stabilize the flame and grows from the wealth of literature on cavity flows (Hsu et al., 1995, Sturgess and Hsu, 1997, Straub et al., 2000, Roquemore et al., 2001). Much of this effort examines the flow field dynamics established by the cavities, as demonstrated in aircraft wheel wells, bomb bay doors and other external cavity structures. Cavities have also been studied as a means of cooling and reducing drag on projectiles and for scramjets and waste incineration (Gharib and Roshko, 1987). Very little work, however, exists on studying cavity flameholders for subsonic flow and none at all for lean premixed operation for potential use in a land based gas turbine engine (Roquemore et al., 2001).

The actual stabilization mechanism facilitated by the TVC is relatively simple. A conventional bluff or fore body is located upstream of a smaller bluff body - commonly referred to as an aft body - at a prescribed distance commensurate with cold flow stabilization studies (Hsu et al., 1995, Sturgess and Hsu, 1997, Roquemore et al., 2001). The flow issuing from around the first bluff body separates as normal, but instead of developing shear layer instabilities which in most circumstances is the prime mechanism for initiating blowout, the alternating array of vortices are conveniently trapped or locked between the two bodies. The very stable yet more energetic primary/core flame zone is now very resistant to external flow field perturbations, yielding extended lean and rich blowout limits relative to its simple bluff body counterpart.

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Due to its configuration, the system has greater flame holding surface area and hence will facilitate a more compact primary/core flame zone; which is essential in promoting high combustion efficiency and reduced CO emissions. Incorporation of transverse struts (Roquemore et al., 2001), which enhance the mixing/interaction of hot combustion products with the cooler premixed fuel and air, further reinforces the merits of the TVC as an excellent candidate for a lean-premixed combustion system.

This paper presents the development of the single TVC concept for lean-premixed combustion at gas turbine conditions starting from the simple bluff body flame stabilizer. The TVC is evaluated based on emissions measurements of NO_x and CO. It is shown that the final TVC design tested demonstrated excellent emissions performance capabilities, rivaling many industrial gas turbine combustors to date under its operation in lean premixed mode.

NOMENCLATURE

ppm	*parts per million by volume*
ppm @ 15% O_2	*parts per million by volume corrected to 15% oxygen dry*
EI_i	*emissions index for species i,* g_i/kg_{fuel}
Φ_{fe}	*front-end fuel-air equivalence ratio, includes TVC fuel and air, neglects liner cooling air*
Φ_{tvc}	*TVC fuel-air equivalence ratio, only considering the fuel and air injected directly into the trapped vortex cavity*
η_{comb}	*combustion efficiency*

EXPERIMENTAL SYSTEM

Testing was conducted at the GASL test facilities. The GASL facility is a blow-down type (Cresci, 1995) that provides nominally 60 minutes of high pressure and temperature testing. Actual stable combustion test time in the present work was 30 minutes. The facility employs a non-vitiated, pebble bed heater to attain the prescribed preheat temperature (761°F, 678 K). The preheated air is then split into three independently metered legs. One leg feeds the intake plenum (main-channel air), another feeds the cooling plenum (cooling air) while the third leg supplies air to the TVC cavity. Like the air system, there are three independent and controllable fuel legs: premixed (main-channel fuel), TVC module fuel, and fuel for the diffusion pilot. Fuel supplied to the combustor is industrial grade methane of 98% purity. At the exit of the combustor, a water quench, four-station emissions probe samples the combustion products (CO, CO_2, O_2, NO, NO_x and UHC), which are all read by independent instruments. A downstream back-pressure valve is employed to set the desired operating pressure independent of mass flow rate. Consult Figures 1, 2, and 3, for a layout of the overall combustion system including internal hardware.

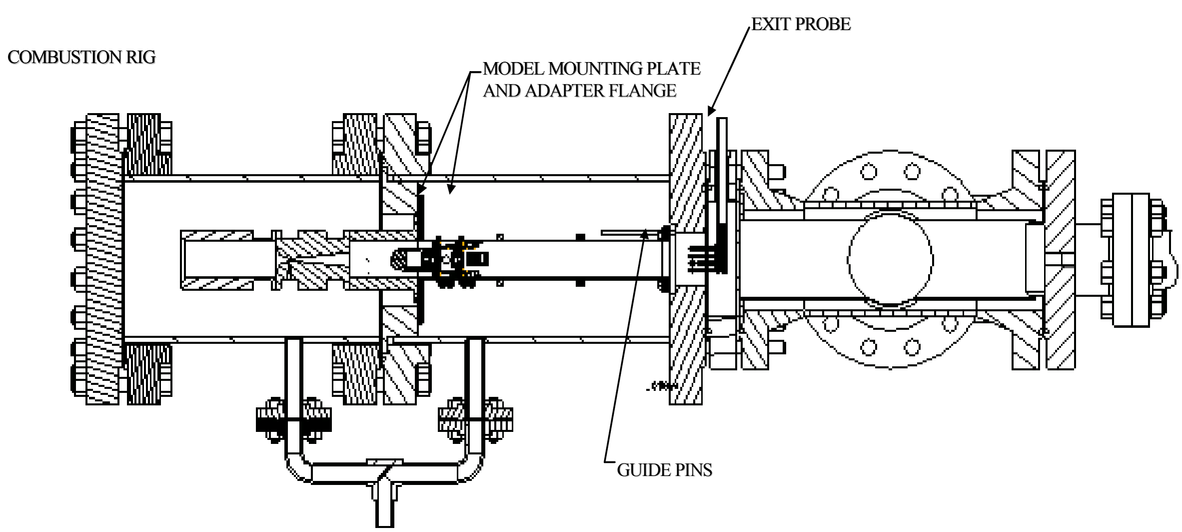

Figure 1: Combustion Rig (pressure vessel and internal hardware).

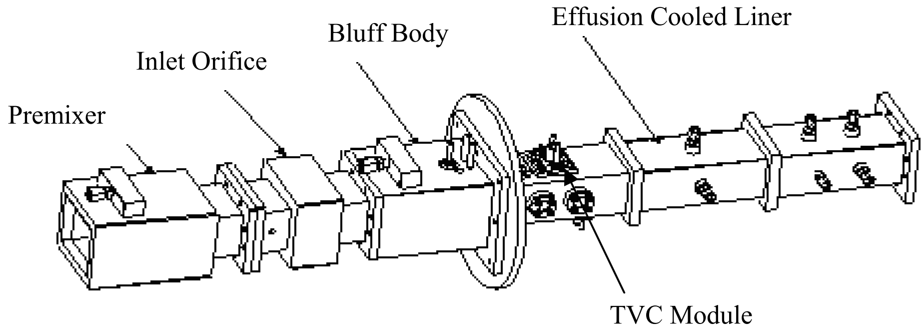

Figure 2: Test Combustor with Sections – this is located in the forward half of the Combustion Rig shown in Figure 1.

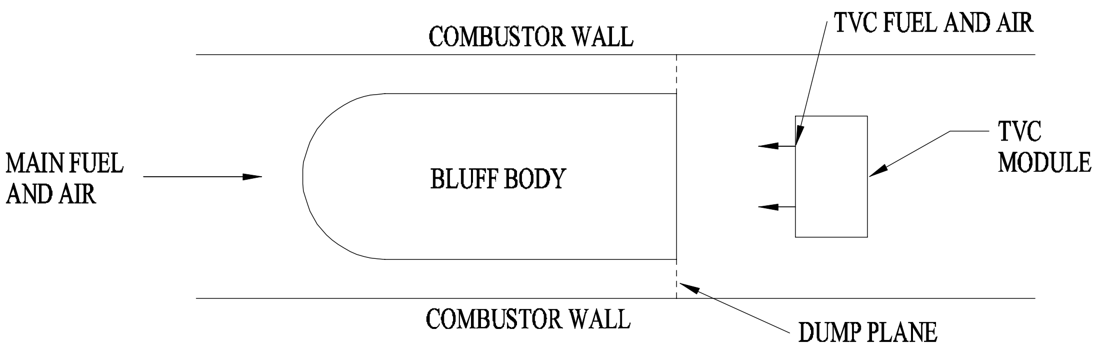

Figure 3: Top View of Bluff Body and TVC Hardware.

The combustor liner (i.e., the effusion cooled liner of Figure 2) defines the exterior limits of the flow path and is the primary mounting point for the TVC module (see Figure 3). A stainless steel forward flange provides for mounting the liner to the cooling plenum head flange. An aft flange supports a piston seal to prevent air loss to the exhaust section. The combustor walls are fabricated from Inconel 625 sheet, sheered and laser welded. The combustor liner interior has a 0.015 in. (0.4 mm) zirconia coating for thermal protection. A variable density effusive cooling pattern is laser drilled on each wall of the liner. Stainless steel type 304 stiffeners are positioned at the third locations to allow the liner to withstand a 15 psia (1.02 atm) pressure differential at the 1800°F (1256 K) design maximum temperature. The above cooling strategies were designed to yield a 1300°F (978 K) average liner temperature.

Static and dynamic pressure transducers are located centrally on each third of the combustor's left side, aft looking forward. Three stainless steel bosses on the combustion liner house quartz windows for viewing the combustion zone. Top and right side, aft looking forward, windows view the region between the bluff body and the TVC body. All of the windows are air film cooled.

The upstream flange of the combustion liner is bolted to a head flange. This head flange separates the cooling plenum from the intake plenum. On the upstream side of the head flange, the bluff body module mounts to the combustion liner flange. Cantilevered off the bluff body module is the pre-mixer module. A restriction screen and the intake nozzle may also be installed between the bluff body and pre-mixer modules. All of these features are suspended in the intake plenum. At the forward end of the intake plenum is a blind flange. This flange contains an 800 psia (55 atm) burst disk and an inspection port.

Air from the intake plenum flows first through the pre-mixer module (Figure 2), which defines a rectangular stainless steel duct with the same internal dimensions as the downstream combustion liner. The leading edges of the duct have radii for flow conditioning. Internal to the duct are three 3/16 in. (4.8 mm) stainless steel fuel tubes. Each tube has seventeen, 0.018 in. (0.46 mm) holes drilled through its wall. Methane is injected normal to the air flow through these holes. Pressure and temperature measurements are taken downstream of the fuel injection point. These measurements are used as a check for auto ignition and flame holding.

Between the pre-mixer module and the combustor is the bluff body. The bluff body's aft face incorporates impingement/effusion cooling and diffusion piloting strategies. The bluff body serves several functions:

- Its aft face is the dump plane of the combustor (Figure 3).
- For the bluff body experiments, it is the flame stabilizer.
- Additionally for the bluff body experiments, pilot fuel is injected from the aft corners of the bluff body. (These diffusion pilots are used only in the bluff body experiments.)
- For the TVC experiments, it serves as the forward face of the trapped vortex cavity.

The TVC module (Figure 3) can be installed through the combustion liner in any of five downstream positions. From the downstream position, the TVC module's independent fuel and air supplies are introduced in opposition to the dominant flow field. The module's width has been sized relative to the bluff body width based on previous trapped vortex experiments (Sturgess and Hsu, 1997, Roquemore et al., 2001). The module's height is determined by the combustor height while its length is determined by the size of internal components. The TVC module's external faces are zirconia coated and effusively cooled. The air and fuel feed lines and the thermocouples are routed through the cooling plenum to connections external to the rig. The condition of the TVC module is monitored by two K-type thermocouples welded to its external face.

The cooling plenum is comprised of two, 12 in. (0.305 m) diameter, schedule 80, carbon steel, pipe sections. The split plenum allows for improved maintenance access. The liner cooling scheme mimics a fixed geometry system, but allows for investigation of off design conditions. To accomplish this, the cooling plenum accepts a 1 in. (25.4 mm), independently metered air line, as well as the majority of the combustor's fuel, air and instrumentation lines. As air enters the plenum, it is diverted by a splash plate to prevent local cooling of the liner. A manual pressure equalization valve can be opened if the cooling plenum pressure exceeds the allowable delta pressure for the liner. In the open position this valve allows communication between the exhaust section and the cooling plenum.

EXPERIMENTAL RESULTS- BLUFF BODY COMBUSTION

Bluff body testing served to provide baseline experience for the later TVC testing by establishing global combustion zone locations, baseline emissions data, and nominal liner cooling flow rates to achieve permissible liner temperatures as dictated by mechanical constraints. Blockage ratios were dictated by standard bluff body correlations (Ozawa, 1970). The nominal, dump plane blockage ratio was kept at 63% throughout the testing program. Baseline operating conditions for both the bluff body and the TVC configurations are show in Table 1.

Table 1: Design Point Operating Conditions

Item	Value
Combustor Pressure [psia (atm)]	275 (18.7)
Inlet Preheat Temperature [°F (K)])	761 (678)
Total Air flow rate [lb/s (kg/s)]	2.367 (1.08)

The initial bluff body testing focused on excursions in diffusion piloting levels, liner cooling flow rates, and flame temperatures. Combustion efficiency was calculated through gas sample measurements of unburned hydrocarbons (UHC) and carbon monoxide (CO) per the following industry standard formula (SAE Report AIR #1533, 1982):

$$\eta_{comb} = 100 \times \left(1.0 - 10109 * \frac{EI_{CO}}{H_c} - \frac{EI_{UHC}}{1000} \right) \qquad (1)$$

whereby the emissions are expressed as emissions indexes (EI) and H_c is the lower heating value expressed in J/kg.

The bluff body tests were conducted at reduced combustor pressure 210 psia (14.3 atm), while maintaining full preheat temperatures (761°F, 678 K) and system air flow rates. The reduced pressure is below the design point pressure of 275 psia (18.7 atm) due to the decision to limit pressure during the initial testing within the rig.

For this testing, a 50% blockage screen was added between the pre-mixer and bluff body modules to further promote fuel-air mixing. The reduced pressure of 210 psia (14.3 atm), relative to the design pressure of 275 psia (18.7 atm), resulted in an approximately 15% drop in the hot-burn residence time, thereby increasing CO emissions. Thus, the CO results are viewed as worse case, since lower CO levels could have been achieved under the design point operating pressure. Such reduced pressure testing may tend to lower NO_x levels due to its pressure dependence (Bhargava et al., 2000, Kendrick et al., 2000), though this effect is less severe than on CO emissions. However, other studies on lean-premixed combustors operating with very low NOx emissions show the NOx as neutral or slightly increasing with decreasing pressure (Steele et al., 1998). Figure 4 shows CO versus NO_x for the bluff body combustor runs at 210 psia (14.3 atm).

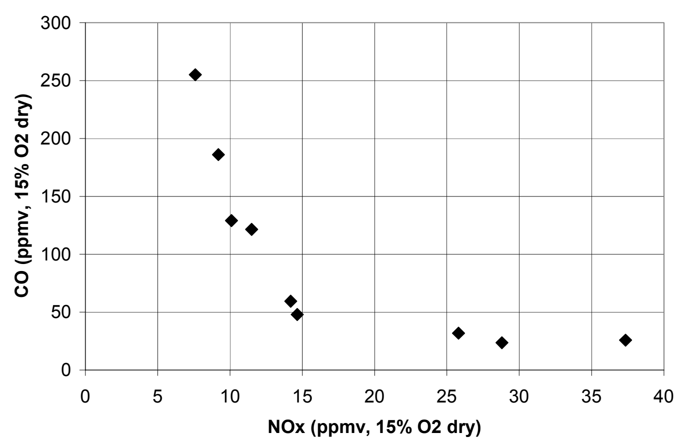

Figure 4: CO vs. NOx for the bluff body combustor run at 210 psia (14.3 atm).

Although full design point pressure was not achieved with the simple bluff body flame stabilizer, very good NO_x emissions and combustion efficiencies were achieved. The CO emissions levels were, however, not sufficiently competitive for gas turbine engines. The CO emissions are high due to the quenching effects of the interaction of the cooler premixed fuel and air with the hot TVC cavity gases and the high surface to volume wall effects of the rectangular burner. An improved backside cooled burner design will aid in reducing the CO emissions. Rather, simultaneous NO_x/CO emissions of about 10 ppm @ 15% O_2 or less must be achieved over a wide operating envelope to ensure product competitiveness within the marketplace and overall design margin. The TVC is now examined as a possible improvement over the simple bluff body to achieve such stringent emission goals.

EXPERIMENTAL RESULTS- TRAPPED VORTEX COMBUSTOR

The TVC concept relies on inhibiting vortex shedding from the bluff body, which can destabilize the primary combustion process and hence prematurely limit the system's operating envelop (Burrus et al., 2001, Straub et al., 2000, Zukoski and Marble, 1955). Wide operating envelopes are highly desired for most combustion systems, especially for land-based gas turbine engines due to part-power requirements. Furthermore, the intense combustion activity existing within the trapped vortex cavity can serve as a mechanism to facilitate the interaction between the cooler premixed fuel and air and hot combustion products, thereby encouraging flame stabilization.

Augmenting the interaction of the highly energetic trapped vortex cavity gas with the cold, co-flowing channel flow is required to fully exploit the benefits of the TVC concept (Roquemore et al, 2001). This can be accomplished by using flame stabilizing features upstream of the dump plane to create a low velocity region allowing for enhanced interaction between the main flow and the trapped vortex cavity (Roquemore et al., 2001). If the burning gas of the trapped vortex cavity is distributed more effectively into the channel flow, enhanced combustion intensity and hence efficiency will result. Furthermore, this heightened interaction should reduce CO emission since ignition is commenced earlier within the combustion liner, thereby allowing more time for burnout. Additionally, the tendency of quenching of CO burnout by the liner cooling air is reduced.

A combustion pressure of 270 psia (18.4 atm) and Φ_{tvc} of 0.75 were maintained during TVC testing. After establishing these baseline conditions, excursions in front-end equivalence ratio were conducted through adjustments of the main fuel flow rate. The mass loading in the TVC cavity was kept below 10% to maintain flame stability and localized control of the metal temperatures.

Proof of the TVC's performance gain is demonstrated in Figures 5 and 6. In Figure 5, the combustion efficiency of the final TVC configuration tested is compared with that of the bluff body. For similar front-end equivalence ratios (that define the fuel-air ratio of the main combustion process), the TVC efficiency is superior to that of the bluff body. Notwithstanding the wall quenching effects which are relatively constant for both the bluff body and TVC configurations, the TVC design has reduced the CO emissions by more than a factor of 10. The reduction in CO emissions is a result of the flame holding features, which increased the fluid mechanic interaction between the premixed fuel and air flow and the hot products of combustion in the TVC cavity. Although kinetic modeling shows that part of the gain by the TVC configuration is due to its higher pressure, the primary effect in the TVC is that of improved flame stabilization by the enhanced interaction between the burning gas of the trapped vortex cavity and the main flow.

As shown in Figure 6, the TVC has made marked improvements on the overall emissions characteristics of the system. Simultaneous, less than twenty parts per million of CO and NO_x @ 15% O_2 is achieved over a useful stoichiometric range, superior to the bluff body performance. Furthermore, the 10ppm NO_x/10ppm CO threshold is achieved. The plot demonstrates both CO generation mechanisms: the tendency towards equilibrium CO concentration for the richer mixtures (higher NO_x) and the kinetic limitation to CO burnout for the leaner mixtures (lower NO_x). The NO_x emission demonstrates typical behavior of increasing NO_x with increasing flame temperature.

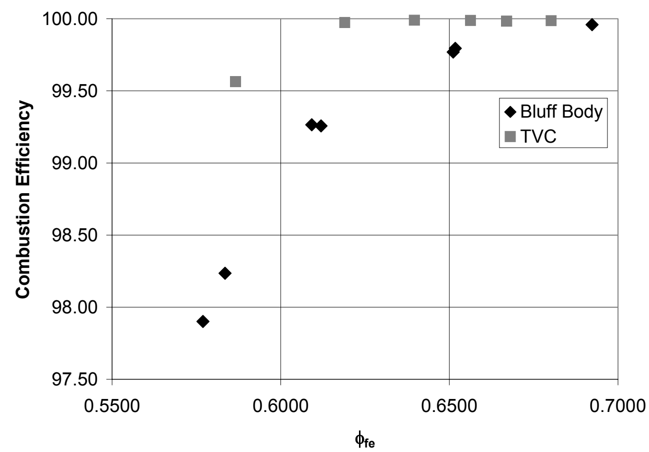

Figure 5: Combustion efficiency versus ϕ_{fe} for the bluff body (210 psia, 14.3 atm) and TVC (270 psia, 18.4 atm) combustors.

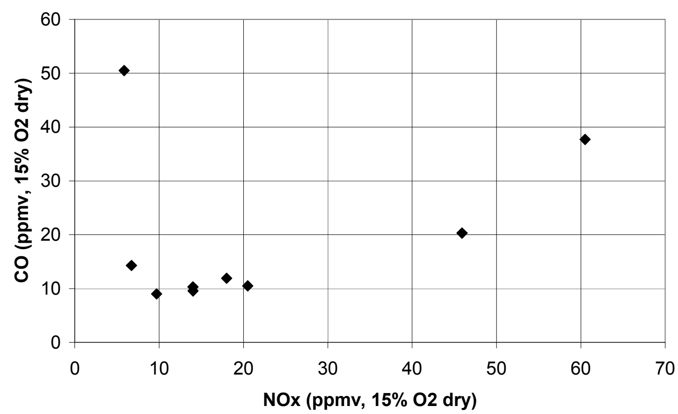

Figure 6: CO vs. NOx for TVC

ANALYSIS

In order to verify the emissions obtained from both combustor configurations, comparison is made to the work of Leonard and Stegmaier (1994). Figure 7 shows a comparison of the experimentally measured NO_x versus the results obtained by applying the results of Leonard and Stegmaier (1994). Leonard and Stegmaier (1994) showed NO_x to be mainly a function of flame temperature for lean-premixed methane-air combustion. In light of this, the experimental results of Leonard and Stegmaier (1994) are fit by a single exponential equation of NO_x @ 15% O_2 versus the adiabatic equilibrium flame temperature. To apply this equation to the present measurements, the adiabatic equilibrium temperatures are calculated for the present conditions of Φ_{fe}, pressure, and inlet temperature. Then these temperatures are used in the equation, and thus, NO_x based on Leonard and Stegmaier (1994) is predicted for the present experiments. For TVC analysis of NO_x, the amount of cooling air entering the flame from the TVC module and combustion liner has been estimated and used to adjust Φ_{fe}. The curve fit equation based on the Leonard and Stegmaier (1994) data was extrapolated to higher flame temperatures to cover the measured parameter space.

Figure 7 indicates the NO_x formed in the bluff body and TVC configurations is close to that expected based on the Leonard and Stegmaier (1994) results. Steele et al. (1998) compared the Leonard and Stegmaier (1994) results to NO_x data for several lean-premixed combustors, both of laboratory scale and of engine scale, and found the Leonard and Stegmaier (1994) results to fall near the lower end of the NO_x data. It follows that the present experiments operated close to the minimum NO_x expected for the flame temperatures run. Additionally, as pointed out in the preceding section, the TVC configuration yielded both minimum NO_x and CO. The CO emissions were greatly reduced due to the greater interaction of the premixed fuel and air and the hot cavity gases which result from the unique flame holding devices installed at the combustor dump plane.

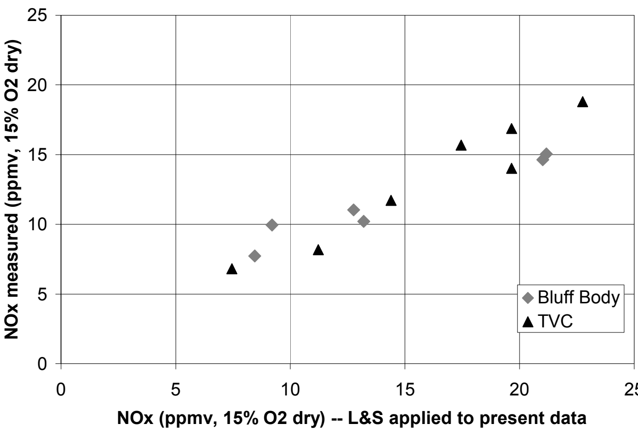

Figure 7: NOx measured versus NOx based on Leonard and Stegmaier (1994).

A CFD study using the commercial code *CFX* was also conducted on both the bluff body and TVC configurations. The code was run in 3-D mode with over 175 million elements and 373 thousand nodes. The study used the simple two-step global reaction mechanism for methane combustion (Westbrook and Dryer, 1981), the k-ε turbulence model and constant wall temperature (1300F, 978 K) boundary conditions. No effusion cooling flow was simulated and TVC fuel and air issued through appropriately sized slots for simplicity. Due to the kinetic simplicity of this mechanism, the CFD was primarily used to understand the flow field dynamics, flame structure and heat release distribution within the combustor and not the CO emissions. Although the Westbrook and Dryer mechanism is a useful tool to predict overall temperature increases and trends in the CO emissions, it is not able to accurately resolve the CO emissions at these low levels of less than 200 ppmv. As a result, the measured CO emissions were not directly compared to the predictions.

It is critical to correctly design the vortex structure in the TVC cavity to determine the optimum fuel injection locations for fuel loading, flame stability and emissions control. In spite of the limitations of using the 2-step mechanism for predicting the flame structure, the CFD solutions did provide valuable qualitative information to more fully understand the vortex structures in the cavity. Figure 8 shows the trapped vortices behind the bluff body. As can be seen in the figure, several distinct vortices are predicted in the TVC cavity, with the main vortex rotating opposite the "natural" direction due to the placement of the fuel and air injection points. Depending on the placement and flow rates of the injection points, cavity vortices rotating in opposition or with the channel flow direction can be generated (Straub et al., 2000). Without the injection of fuel and air from the upstream face of the TVC module one would expect to see a single vortex rotating clockwise in Figure 8.

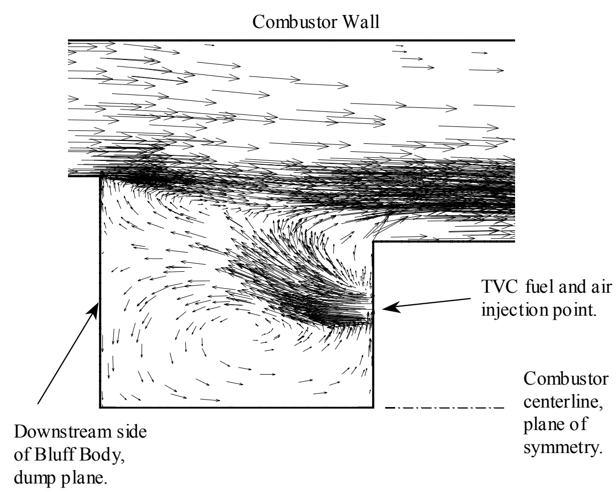

Figure 8: Flow field predicted by CFD in upper half of the TVC cavity.

CONCLUSIONS

Combustion testing on lean-premixed bluff body and TVC configurations has been conducted. Testing commenced on the simple bluff body flame stabilizer with a 63% blockage ratio with expected levels of success. Combustion efficiencies above 99% were routinely achieved but competitive combustion exhaust gas emissions were not obtained for CO. The next test series evaluated the TVC concept, which relies on locking a vortex structure between the fore and aft bodies of the cavity. Interaction between the highly turbulent, hot cavity gas and the cold channel flow is promoted using flame stabilizing features placed in the channel flow. By this approach, emissions of 10 ppmv NO_x/10 ppmv CO and high combustion efficiencies (>99.9%) are obtained. These results indicate the success of the premixed TVC for possible implementation into an industrial gas turbine engine. New testing planned will permit the lean-premixed TVC to be refined, and for its ultimate emissions reduction potential to be ascertained.

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