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EXPERIMENTS ON LEAN BLOWOUT AND NOx EMISSIONS OF A PREMIXED TRAPPED VORTEX COMBUSTOR WITH HIGH G-LOADING

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ABSTRACT

The feasibility of a novel combustor concept (‘g-load’ combustion with trapped-vortex chamber) to extend the premixed lean-blowout (LBO) limit and to decrease NOx emissions was experimentally determined in a scaled-modular rig that simulated a commercial 250 kilowatt microturbine combustor. The effect of a wide range of g-load’s (770-5050) on the flame regime was identified. The natural gas flame was found to be stabilized in the trapped-vortex cavity (TVC) when the equivalence ratio was within a certain range near the lean blowout limits. The TVC extended the LBO limits to marginally lower mass-based equivalence ratio levels (5%). The LBO limits were found to decrease as the g-loads decrease and the residence time increases, indicating the increase of flame mixing and reaction rates with respect to g-load is not the reason for the extension of LBO limits. The increase of residence time of mixture in the TVC was the reason for the improvement of LBO limits. The new combustor concept would enable operation at lower equivalence ratios, reducing the NOx emissions as much as much as 30%. It also showed that when the flame is contained in the trapped vortex cavity, NOx is reduced compared to baseline combustion concept without TVC.

NOMENCLATURE

D_s	=	swirler diameter
g	=	acceleration of gravity
g_{load}	=	g-load of the fuel/air mixture
G_m	=	axial flux of angular momentum
G_t	=	axial thrust
P_3	=	compressor discharge pressure
ρ	=	density
r	=	radius
r_{trap}	=	radius at base of the TVC
Q	=	volumetric flow rate
SN	=	Swirl Number
τ_{res}	=	residence time in trap (ms)
T_i	=	combustor inlet temperature
T_3	=	compressor discharge temperature
U_θ	=	tangential velocity
U_z	=	axial velocity
V	=	combustor volume
V_{trap}	=	volume of trap cavity
W_a	=	compressor mass flow rate
Ω	=	combustor aero loading

INTRODUCTION

Lean premixed (LP) combustion in a swirl-stabilized combustor is a proven concept for emissions reduction in industrial gas turbines. Gaseous fuel and air are uniformly mixed prior to combustion. The premixed fuel/air reacts at fuel lean conditions, reducing the amount of NOx formed from the thermal NOx mechanism.

In order to minimize the production of thermal NOx, it is necessary to design a combustor’s primary zone to react fuel and air at a temperature as low as possible. Minimizing emissions necessitates operating near lean blowout stoichiometric conditions. One common approach to avoiding lean blowout is to inject a small portion of the fuel flow directly into the combustor. This creates a diffusion flame to locally richen the fuel/air ratio. This increases the static stability or lean blowout margin. This paper’s use of the term “static stability” should not be confused with combustion dynamic instabilities, which result from the coupling of heat release and pressure waves. The increased static stability from a pilot flame bears the cost of higher NOx emissions. This study investigated a method to improve the static stability without the use of a pilot diffusion flame.

The traditional gas turbine flame stabilization mechanism relies on swirl-stabilization, where strong swirl above a swirl number of 0.6 is needed to establish a vortex breakdown flow structure. Lefebvre [1] defined swirl number as:

$$\textit{Swirl number} = \frac{\int_{R_i}^{R_o} U_\theta U_z r^2 dr}{R_o \int_{R_i}^{R_o} U_z^2 r dr}$$

A flow reversal is established behind a center bluff body and a dump plane where hot products of combustion are recirculated and mixed with fresh mixture. This highly turbulent flow serves to continuously ignite the unburned LP gases flowing at the boundaries of the swirling flow, thereby stabilizing the flame.

Classical swirl-stabilized LP combustion with pilot fuel stabilization is currently employed in the Flex Energy MT250 microturbine to achieve low emissions. To investigate a potential improvement to this combustion system, a trapped vortex combustion concept with a high g-load was investigated in a university laboratory. Trapped vortex combustors (TVC) have been investigated by a variety of researchers as a potential feature to improve combustion stabilization. This concept typically employs a recess or cavity, built either into the wall of a duct, or downstream of a bluff body, and equipped with a plurality of fuel and air supply holes. One or more vortical structures are established inside the cavity that circulates the fuel and air, establishing low velocity and high residence time for combustion. A significant advantage of TVC's is its resistance to main flow fluctuations.

Hsu et. al. [2] reviewed the history of trapped vortex cavity research, most of which was focused on the flame stabilization in high velocity applications; typically afterburners. Hsu stated that there is little exchange of fluids between the cavity and the main stream flow. They asserted that this would lead to poor flame stability in the trap. Flame stability requires a continuous exchange of mass and heat between the cavity and the main flow. Their approach to solving this issue was to directly inject fuel and air into the trap cavity. The lowest lean blowout limits corresponded to low air injection rates, which the authors attributed mixing and residence time increases.

Haynes et. al. [3] investigated a TVC in a can-annular gas turbine application. They combined both traditional swirl-stabilization with an annular TVC. Their trap cavities could be fueled as either a diffusion flame or with premixed fuel and air. Two different sized traps were tested. The largest trap provided superior lean stability, while the smaller trap minimized NOx production at higher power, richer conditions. The lowest NOx performance was with a premixed fuel mode.

Edmonds et. al. [4], [5], investigated a premixed trapped vortex cavity anchored behind a bluff body at elevated pressures. Their trap was independently supplied with fuel and air. They desired a stable vortex in their TVC with minimal vortex shedding. However, for flame stabilization in the TVC to work correctly, they noted that lateral mixing from the TVC region into the main flow is required. Edmonds found that CO emissions were reduced as a result of flame holding features that promoted interaction between the premixed main flow and the TVC products of combustion.

Researchers of TVC's share similar conclusions that a good design requires both a stable vortex and a fluid exchange mechanism between the trap and the main flow. The concept investigated herein combines a trapped vortex combustor with a high g-load fluid exchange mechanism. The term "high g-load" refers to combustion taking place where a large body force, established by fluid rotation and centrifugal effects, serves to promote fluid exchange into and out of a trapped vortex cavity.

Lewis [6] studied the effect of combustion in the presence of a large centrifugal force. Lewis measured the propagation rate of the flame, as measured with ionization probes, and showed that their observed flame propagation rate can exceed values of turbulent flame speed. He used the term "bubble velocity" to describe the very rapid speeds of the flame propagation in the presence of a centrifugal force. He attributed the high velocities with the force acting against a density difference (buoyancy) between the unburned reactants and burned products of combustion. He normalized the centrifugal force relative to the gravitational constant, hereafter referred to as g-load. Lewis measured an increase in bubble velocity from a g-load of 500 to 3500 g's for premixed propane/air and lean mixtures of hydrogen/air. However, above 3500 g's, the flame propagation rate markedly decreased. The maximum bubble velocity at 3500 g's was approximately 3 to 4 times higher than turbulent flame speeds of propane/air mixtures [6].

Zelina et. al. [7] used an unsteady, laminar CFD simulation of a hydrogen flame to support the buoyancy mechanistic explanation of Lewis. G-loads of 10 g's and 500 g's were analyzed. The 10 g case demonstrated uniform, laminar flame propagation. The 500 g case showed a non-uniform flame front propagating approximately five times faster. Their simulation supported the idea that a density gradient in the presence of a g-load would promote movement of burnt products of combustion into unburned regions.

The Combustion Branch of Wright Patterson Air Force Base has investigated leveraging the high stability of a TVC combined with the mixing and exchange mechanisms of high-g loads with the Ultra Compact Combustor (UCC) concept [7]-[9]. They directly injected liquid fuel (JP8+100) and air into a TVC with high g-loads. They measured high levels of heat release rates and combustion efficiency. They acknowledged the important issue of understanding how much main air was entrained into the cavity, stating that this entrainment will impact stability and operability in the cavity at low power, lean conditions. Importantly, high g-loads were shown to reduce the stability of the cavity combustion, resulting in richer LBO mixtures. Similar results will later be shown in this study.

Zelina [8] interestingly found different flame regimes with respect to flame location with cavity equivalence ratio. Equivalence ratio in this paper is defined as the fuel/air mass ratio normalized with the stoichiometric ratio. He noted a change in the flame location from trapped vortex cavity to a channel cut in a turbine vane used to spread the flame across a high velocity channel to burning downstream. We will later note changes to the flame characteristics in this paper as the LP flame is further leaned.

Yonezawa et. al. [10] tested a "jet-swirl combustor" which also leveraged the high g-load effect to increase combustion efficiency for an annular, liquid-fueled combustor. They measured combustion efficiency relative to combustor air loading parameter, as defined with:

$$\Omega \propto \frac{W_a}{P_3^{1.8} V e^{\left(T_3/300\right)}}$$

They measured higher combustion efficiencies with the jet-swirl combustor as compared with conventional combustors.

Zhang et. al. [11] studied a liquid fuelled TVC, with both fuel and air supplied. They also used the g-load generated by a circulating combustion pattern to improve the static stability of a gas turbine combustor. They demonstrated low overall combustor equivalence ratios at LBO, but their combustor included dilution airflow, so direct comparisons of primary zone LBO numbers are not appropriate.

The research history on TVC's demonstrates that independently fueled and air-supplied TVC's can demonstrate superior lean combustion efficiency and static stability with respect to conventional, swirl-stabilized combustors. However, microturbine applications require a simplified, cost-effective approach to reducing emissions. The MT250 microturbine is a recuperated cycle with a 4:1 pressure ratio. Its combustor inlet temperatures approach 600 C, making modulation of airflow into a trap cavity difficult with high reliability, low-cost valves. Hence, a TVC design that has neither fuel nor air injected into the cavity was desired for simplicity.

In addition to the desire for mechanical simplicity and reliability, low emissions are a strong product advantage of microturbines relative to competitive technology, such as reciprocating engines. An LP combustor with high static stability would enable further reductions in NOx as regulatory pressures continue to advance.

The goal of this study was to determine the feasibility of an advanced combustor concept ('g-load' combustion) to extend the lean-blowout (LBO) limit of biogas-fueled microturbines. Prior to biogas-fueled study, a natural-gas fueled study was made as a preliminary investigation. In order to achieve the goal, a modular, scaled combustor rig of the MT250 combustion system is designed and fabricated, a CFD code is used to determine the g-loading of the rig with and without the TVC feature. The flame structure under various flow conditions and 'g-load' is characterized to understand the effect of 'g-load' and TVC on the overall combustor performance. The combustor performances (LBO limits and NOx emissions) are measured as a function of g-load for various power loads to determine if the LP TVC concept extends the LBO limit to minimize NOx emissions

COMBUSTION CONCEPT

The TVC combustor concept investigated in this research represents an innovative attempt to improve upon the baseline, LP combustion concept. To understand the TVC concept, first consider the baseline technology. The current LP combustor technology used in the MT250 microturbine is schematically illustrated in Figure 1. The cross-section shows a single can or silo combustor, with the axis of revolution illustrated along the centerline. The actual physics of the combustor are highly turbulent, three-dimensional and temporally dynamic with a processing vortex core and different length scale structures. However, the following simplified processes are offered to describe the mixing and combustion sequence with swirl stabilization:

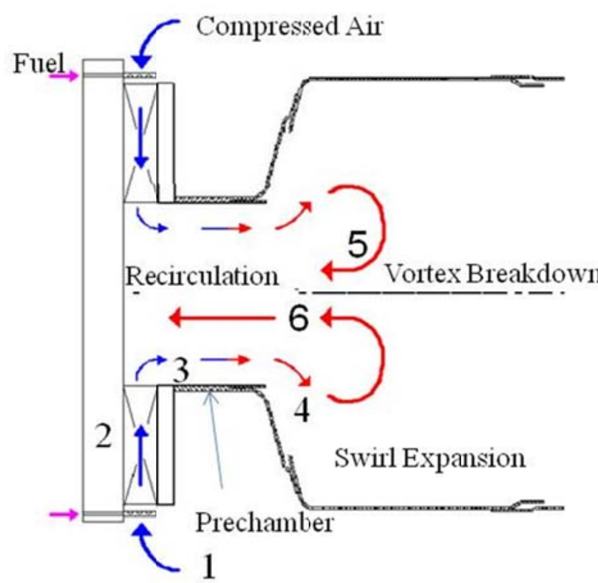

Figure 1: Baseline microturbine combustor

1) Gaseous fuel injected into compressed air from the recuperator
2) Fuel mixes with air to achieve a relatively uniform, lean mixture in a radial swirler
3) Mixture is swirled and injected into the prechamber
4) Swirling mixture, which is heated by a shear flow located at the center of the swirling flow ('6') ignites and rapid generation of heat occurs.
5) Combusting gases enter a flow expansion, where gases decelerate axially and "vortex breakdown" occurs.
6) Hot gases are pulled into the center of the prechamber vortex, which is at a lower pressure than the outside of the vortex. This results in a flow reversal, pulling hot combusted gases backwards.

To improve the flame stabilization, a trapped vortex feature is strategically situated in the prechamber, as illustrated in Figure 2. The TVC cavity serves as a second flame stabilization feature. The first three flow processes are identical to Figure 1:

4) Swirling, premixed fuel and air, flowing from left to right is bordered on the inside ('7') by the shear layer caused by the gases flowing in the opposite direction. The unburned premixed fuel-air mixture is also bordered at its outer diameter by a recirculation zone in the TVC ('5').
5) A circulation zone is set up in the trapped vortex cavity ('5'). There is an exchange of fresh, unburned fuel-air reactants from the inner flow ('3') into the trap and a flushing of burned gases out of the trap.
6) Combusting gases enter a flow expansion, where gases decelerate axially and "vortex breakdown" occurs.
7) Hot gases are pulled into the center of the vortex, which is a lower pressure than the outside of the vortex. This results in a flow reversal, pulling hot combusted gases backwards.

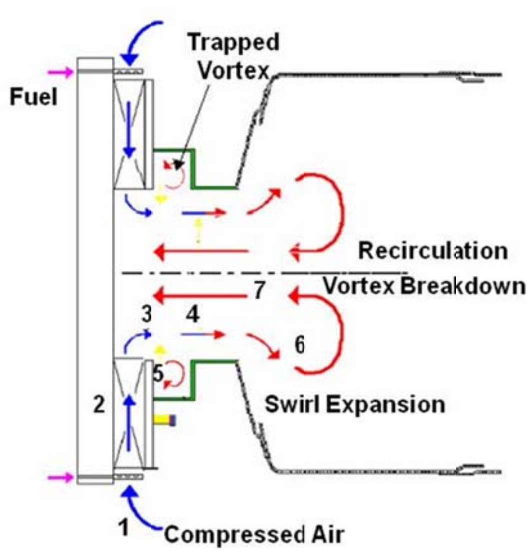

Figure 2: High G-load TVC Combustor Concept

One of the important aspects of this concept is the mechanism that drives the exchange of flows radially in and out of the TVC. The high level of swirl in the prechamber establishes a centrifugal body force in the radial direction. This force promotes the exchange of unburned, relatively colder, higher density fuel/air mixture in the prechamber with the burned, hotter, lower density products of combustion in the TVC. A force pushing a higher density fluid into a lower density fluid sets up a Rayleigh-Taylor instability. This instability ensures exchange will take place, despite the uniform axisymetric geometry of the prechamber and TVC annulus. The radial force pushes the fresh fuel/air mixture into the TVC, which in turn, ejects the hot products of combustion back into the prechamber. A continuous new supply of hot products are mixing back into prechamber flow, serving as another continuous source of ignition.

RIG DESCRIPTION

A scaled, modular test rig that simulates the MT250 combustor was designed and fabricated (Figure 3). Various features were implemented to address the objectives. These included:

- Three radial vane sets with different thickness (22.2, 29.8, and 40.0 mm) to change 'g-load' of the fuel/air mixture
- Operation with and without the TVC
- Optical access to the TVC

The approach to changing the g-load was to vary the radial swirler thickness (h, Figure 3b), while maintaining the swirler passage width thickness (w, Figure 3b) constant. Natural gas and air were premixed prior to injection into the inlet adapter. By maintaining a constant mass flow through the swirler, the tangential velocity of the mixture entering the prechamber could be decreased with thicker radial vanes, while the axial velocity through the prechamber (continuity) remained constant with a constant mass flow rate. This varied the g-load inside the prechamber.

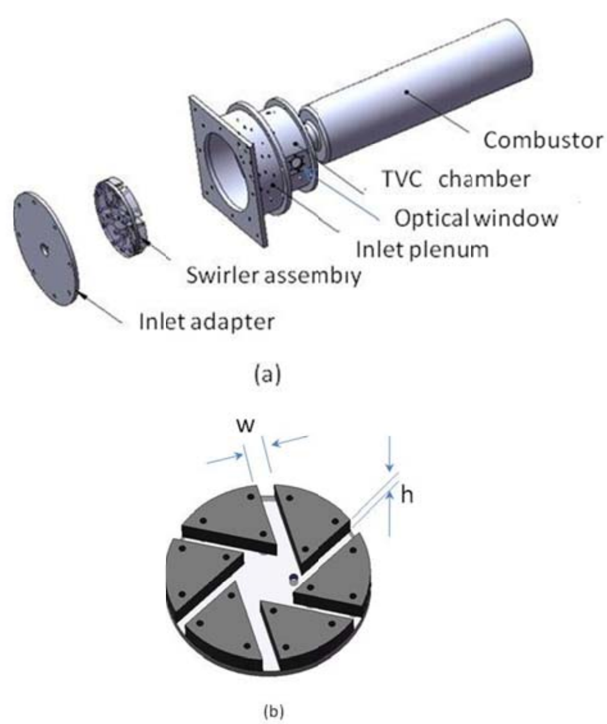

Figure 3: Modular Rig Design: (a) view of exploded combustor assembly and (b) radial swirler configuration

The dimensions of the combustor rig swirler were customized in order to closely simulate the swirler aerodynamics of the full scale microturbine combustor. The number of slots was reduced to six in order to maintain a reasonable slot aspect ratio. The flow conditions were determined in order to maintain a similar average axial velocity in the scaled prechamber. This ensured that timescales would be similar.

The important rig dimensions are shown in Table 1:

Table 1: Rig Dimensions

Swirler slot width (mm)	16.7
Swirler slot height (mm)	22.2, 29.9, 40.0
Swirler outer dia. (mm)	200.0
Prechamber inner dia. (mm)	66.9
Combustor inner dia. (mm)	150.0
TVC outer dia. (mm)	200.0
TVC length (mm)	75.0

Figure 4: Photograph of assembled combustion system

EXPERIMENTAL MEASUREMENT

Exhaust gas was sampled using a water-cooled gas sampling probe (Type B, United sensor) and cooled to quench further reaction using an ice-water bath. NOx emissions were measured using a chemiluminescence NO-NO_2 analyzer (Model 42H, Thermo Environmental Instruments Inc.). It was calibrated using a span gas (40 ppm NO, balance N_2) and its detection limit was specified as 50 ppb.

An attempt was made to measure unburned hydrocarbons to determine LBO. Measurements were performed using a heated hydrocarbon analyzer (Model 300 HFID, California Analytical Instruments, Inc.) to detect LBO limit. However, it was found that the concentration of detected HC was almost zero at near visually-observed LBO conditions. Therefore, LBO limits were defined based on visual observation of flame.

The overall flame structure was characterized and flame regimes were identified for various flow conditions from visual observations of flame through an optical port mounted on the side of the trapped-vortex chamber and recorded using a digital camera.

FLOW FIELD QUANTIFICATION

The magnitude of 'g-load' and swirl number was evaluated for the fabricated experimental setup using a commercial CFD code [12]. The model is a standard Reynolds-averaged, Navier-Stokes simulation. This code uses a standard k-ε turbulence submodel. Analysis of both the full-scale MT250 combustor and the various configurations of the rig combustion system were performed. As shown in Figure 5, a Cartesian grid was used. Figure **5** shows a portion of the model, which covered the entire length of the combustor down to the flow contraction seen at the top of Figure 4. It is acknowledged that modeling an axisymetric geometry with a Cartesian grid can result in less accurate results due to numerical diffusion.

The CFD package did not have the capability to model chemical reactions. It is acknowledged that a CFD tool, capable of simulating chemical reactions would have produced a more accurate model. Further CFD investigations are recommended into this configuration.

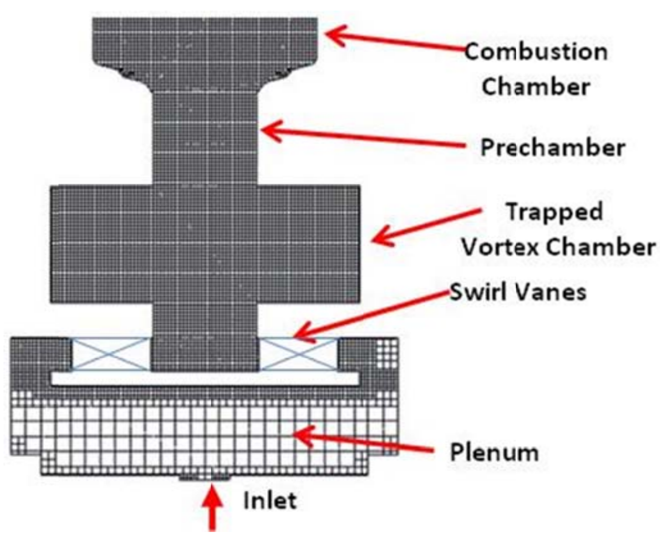

Figure 5: CFD Model of the Rig Combustor with TVC feature

With the g-loaded TVC concept, the buoyancy effects are critical to the exchange mechanism of the prechamber and TVC. Virtual volumes (sphere, torus), permeable to flow, were inserted into the model as shown in Figure 6. The CFD treated these volumes as constant temperature volumes. Therefore, whenever the premixed fuel/air ratio entered these volumes, the temperature was instantaneously increased to a temperature representative of combustion products near lean blowout. Flow exiting these volumes at 1500K was subject to mixing with the fluid around it. Hence, fluid properties such as specific heat and viscosity were a function of local temperature. 1500K was chosen as an approximate temperature near LBO. Andrews [13] reviewed fundamental weak extinction temperatures of premixed flames. He cited an unstretched limit flame temperature of 1534K correlated the lean limit data of Hustad and Sonju [14] from 300K to 800K for methane-air. The 1500k approximation of this CFD analysis assumes the reaction has sufficient time to combust, which may not necessarily be realized near lean blowout, where reactions are slow. However, the residence times in the trap cavity were relatively long, somewhat justifying this simplification.

Another virtual volume added to the model included a cylinder in the prechamber. This was used in post-processing to measure the g-load at the interface between the prechamber and the TVC, the fluid exchange rate into and out of the TVC, and the prechamber exit swirl number. This measurement cylinder is highlighted in Figure 6.

The g-loads were calculated at the interface between the prechamber and TVC using:

$$g_{load} = \frac{U_\theta}{r_{trap} g}$$

where U_θ is the average tangential velocity, r_{trap} is the radius of inlet to the trapped vortex chamber (33.8 mm) and g is the gravitational constant.

The volumetric flow into the TVC and leaving the TVC is different due to the temperature rise within the cavity. However, for simplicity, the authors chose to define the residence time τ_{res} inside the TVC as:

$$\tau_{res} = \frac{V_{trap}}{Q}$$

where V_{trap} is the volume of the TVC, and Q is the flow rate into the TVC. The CFD radial velocities were used to derive the volumetric flow rate using the area-weighted radial velocities at cylindrical surfaces of the virtual volume of Figure 6. Experimental validation of the fluid flow was outside the scope of this program.

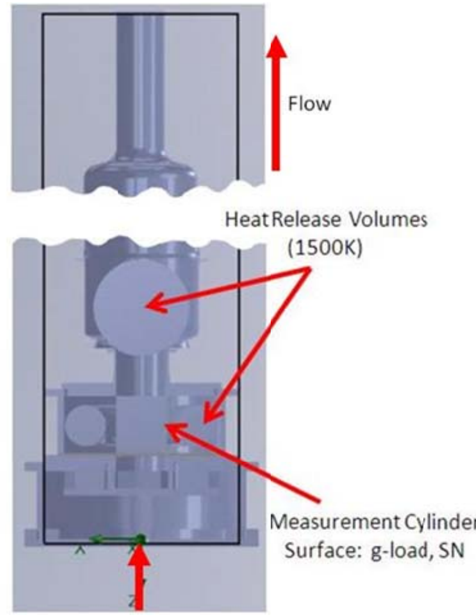

Figure 6: CFD Model with virtual volumes to capture combustion heat release near lean blowout

The CFD analyses of test rig are performed for all cases with the following input parameters:

- Inlet temperature: 400C
- Equivalence Ratio: 0.5
- Combustor pressure: atmospheric
- TVC cavity dimensions: 68 mm (ID) x 203 mm (OD) x 76 mm (length).
- Flame temperature: assumed to be 1500K (Figure 6)

Figure 7 and figure 8 show results of the CFD calculated g-load and residence time of the flow inside the trap. The g-load ranges from 770 to 5050 g's over the range of mean velocity and thickness of vanes listed in Table 2. For a given mean prechamber axial velocity, the g-load decreases as the vane thickness increases and for a given vane thickness, it increases as the mean velocity increases. The TVC residence times, estimated from the CFD, were 60-130 msec. It decreases as the mean velocity increases for a given vane and increases as the vane thickness increases for a given flow rate.

RESULTS AND ANALYSIS

The overall flame structure near lean blowout conditions was characterized and flame regimes were identified for various flow conditions shown in Table 2 from visual observations of the flame through an optical port mounted on the trapped-vortex combustor. No noticeable combustion dynamic oscillations were observed over the range of test conditions listed in Table 2.

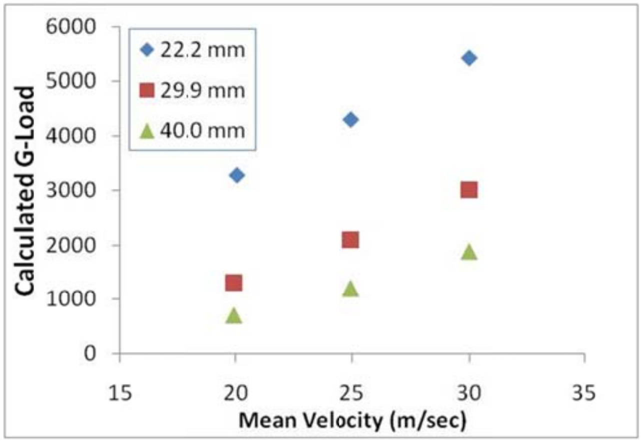

Figure 7: Effect of Vane Thickness of Swirler on 'g-load'

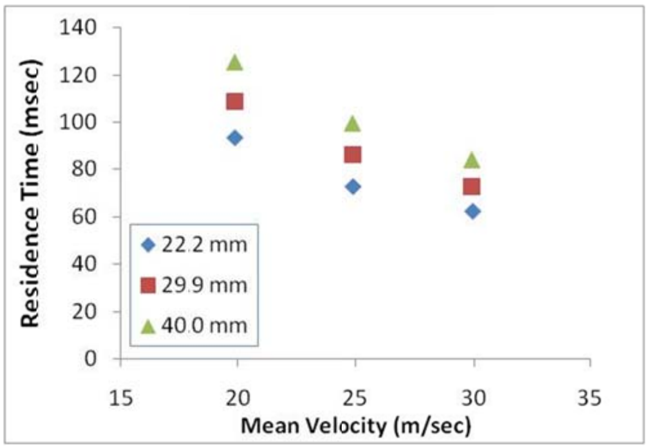

Figure 8: Effect of Vane Thickness of Swirler on Residence Time in Trapped Vortex Cavity

Table 2: Rig Test Conditions

Inlet temperature	400C
Mean axial velocity at the inlet of TVC	20, 25, and 30 m/s
Swirl vane thickness	22.2, 29.9, and 40.0 mm

Without the TVC (baseline case), a tornado-like flame is observed in the center axis of the transition piece and the flame exists mainly in the sudden expansion region of the combustor. As the equivalence ratio is decreased, the tornado-like flame disappears and the flame is lifted off the expansion region. As the equivalence ratio is decreased further, the flame seems to be pushed out towards the combustor exit as shown in image#3 of Figure 9, starts to be observed in the tail pipe and eventually blows out.

Figure 9 shows typical flame images observed through an observation port in the cavity (images #1 & #2) and combustor with the TVC for the mean velocity of 30 m/sec, the inlet temperature of T_i=400C and the vane thickness of 40.0 mm, corresponding to the g-load of 1912. At an equivalence ratio greater than 0.525, the flame is observed mainly in the center axis of the prechamber and the expansion region of combustor. As the equivalence ratio is decreased, the flame starts to fill in the top part of the trap cavity as well and a larger portion of the trap cavity. At the same time, a smaller portion of the prechamber axis is filled with flame as shown in image#1 of Figure 9 which is taken through an observation window on the TVC wall (Type I flame). The image #1 flame shape is shown schematically in Figure 10. As the equivalence ratio is decreased further, the flame eventually disappears at the centerline of the prechamber and is observed only in the trap cavity as shown in image#2 of Figure 9 and Figure 10 (Type II flame). At the lower equivalence ratio, the flame is no longer observed in the cavity section, and is observed only in the main combustor and pushed out towards to the combustor exit as shown in images #3-5 of Figure 9 (Type III flame). If the equivalence ratio is decreased further, the flame starts to be observed in the tail pipe and eventually blows out (LBO limit).

Based on the aforementioned visual observations, maps of flame regime were identified for various mean velocities and vanes as shown in Figure 11. The higher the mean velocity, at the higher equivalence ratio a transition from one regime to the other occurs. For a given mean velocity, the transition occurs at different equivalence ratios if the thickness of vanes (hence g-load) are different.

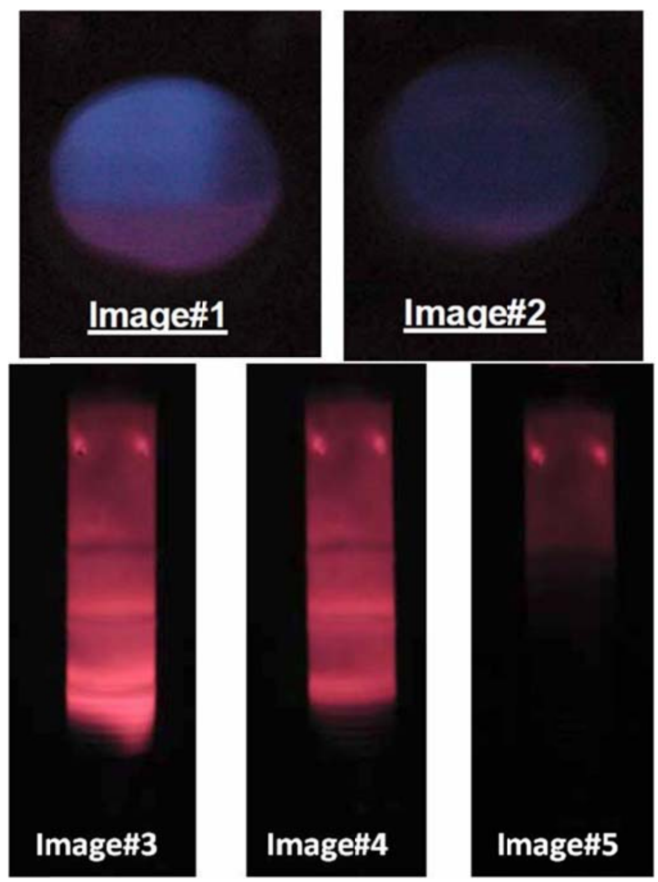

Figure 9: Images of Flame Characterization at 400C, g-load=1912, axial velocity = 30 m/s.

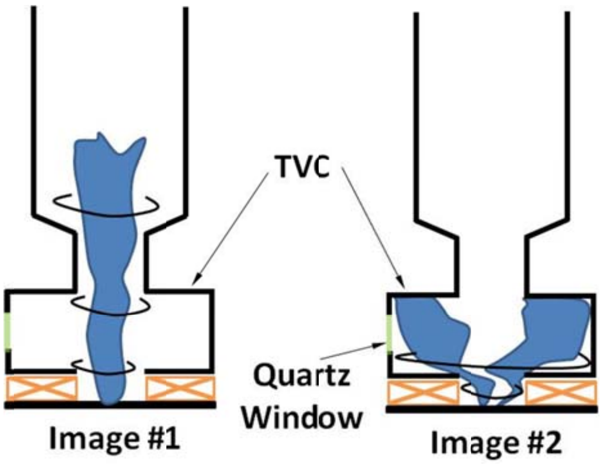

Figure 10: Schematic of observed flame shapes for Type I and Type II flame structures

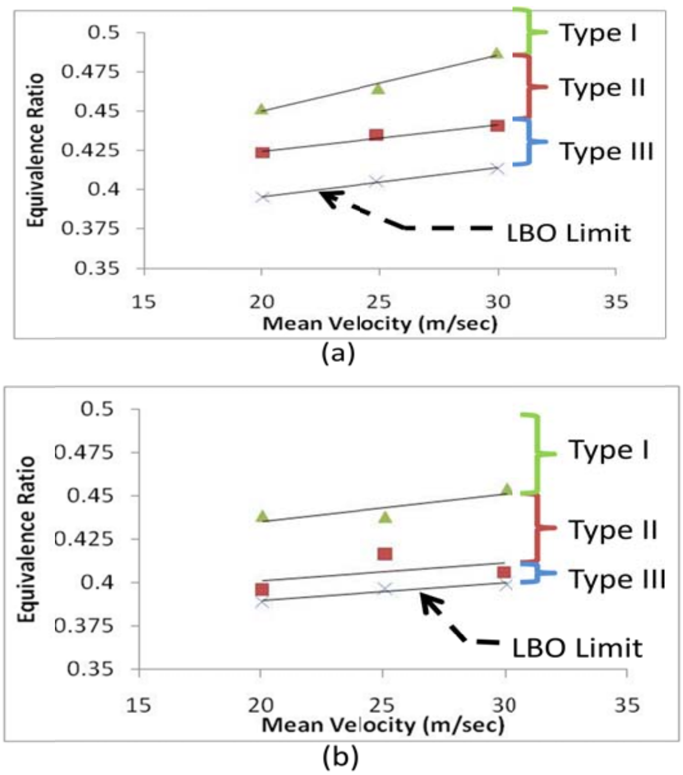

Figure 11: Maps of flame regime for various mean velocities for vanes with thickness of (a) 22.23 mm and (b) 40.01 mm

The overall combustor performance parameters such as lean blow out (LBO) limit and NOx emissions at the exit of combustor were measured experimentally and the effects of 'g-load' and the TVC on them were evaluated. Figure 12 shows LBO limits as a function of mean velocity for vanes with various thicknesses without- and with- TVC. As expected, LBO equivalence ratios increase as the mean velocity increases. The existence of TVC extends the LBO limit to lower equivalence ratio for all cases and its effect on the extension of LBO limit is as much as 5%. In order to determine the causes of the improved LBO limit with the TVC, the LBO data are plotted in different forms as shown in Figure 13 and Figure 14. Figure 13 shows that the LBO limits increase as the g-loads increase, indicating the increase of turbulent velocity with respect to g-load as found in Lewis is not the reason for the extension of LBO limits. Zelina [7] measured similar results in his diffusion-fueled TVC experiments, with higher equivalence ratios needed at higher g-load. Figure 14 shows that the LBO limits decrease as the residence time increases for all vanes, suggesting the improvement of LBO limits is mainly due to the increase of residence time of mixture in the TVC.

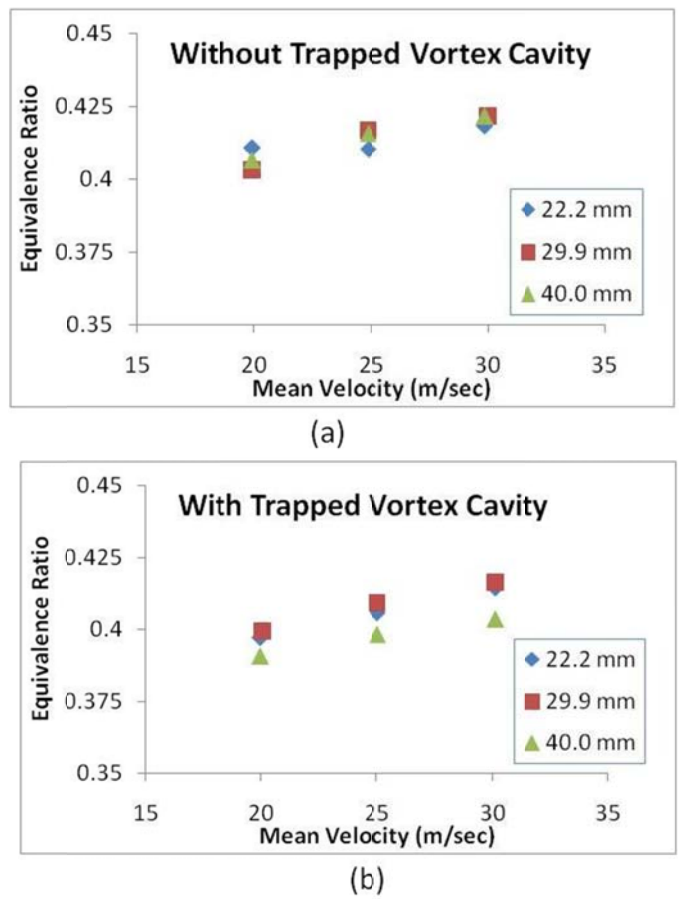

Figure 12: Lean blow out (LBO) limit vs. mean flow velocity for various vanes (a) without TVC and (b) with TVC

Figure 15 shows measured NOx emission measurement results (mean and standard deviation) for combustor without TVC at the mean velocities of 20, 25 and 30 m/sec. It should be noted that the most of the NOx emissions are accounted for by NO_2 with minimal NO. The individual NOx data points for the three mean velocities are all within 6% of each other, and are not shown individually. Instead, Figure 15 shows the NOx data with a 6% error band around each point. Based on the established relationship between NOx and equivalence ratio in Figure 15, a 5% decrease in operating equivalence ratio, enabled by an extended LBO limit, would yield a decrease of NOx emission of approximately 30%.

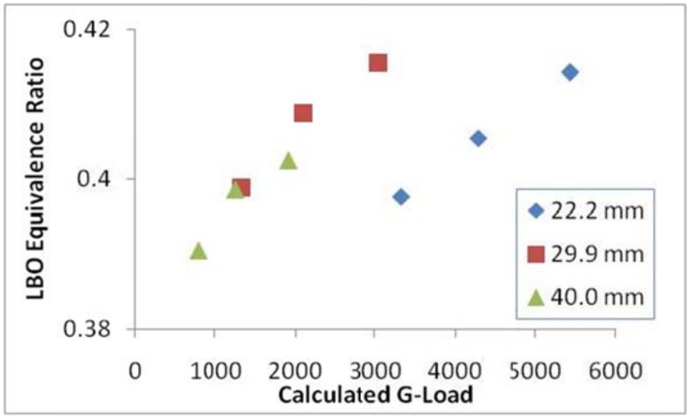

Figure 13: Lean Blow Out (LBO) Limit vs. G-load

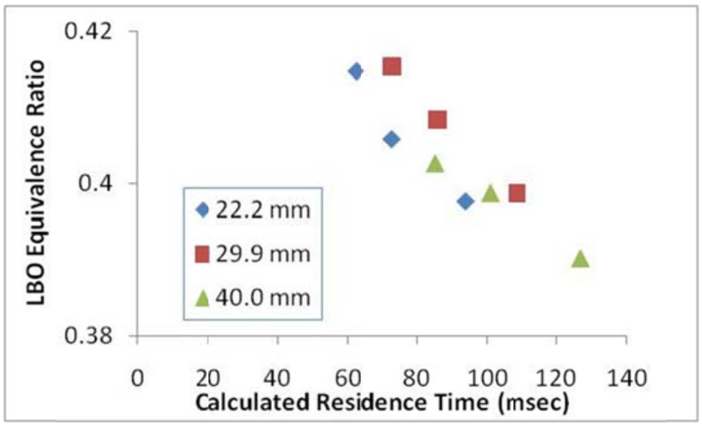

Figure 14: Lean Blow Out (LBO) limit vs. Residence Time

Figure 15 shows the NOx curve of Leonard and Stegmaier [15] for reference. They presented NOx as a function of flame temperature over the operating pressure from 1 to 30 bar, the inlet air temperature from 300 to 800K and the residence time from 2 to 100 msec. The data in Figure 15 were estimated by calculating the equilibrium flame temperature for a 400C, 1 atm. inlet condition. The exhaust oxygen composition was used to correct the measured NOx to the 15% O_2 standard for gas turbine comparisons. The data from the rig combustor without the TVC show a different NOx characteristic than Leonard et. al. One potential explanation would be the cooling effect of the walls may be reducing the flame temperature, which is calculated under an adiabatic assumption. Flame temperatures in the rig were not measured. An additional issue is that the Leonard curve was generated down to 1700K, and the curve in Figure 15 is extrapolated below this value.

Figure 16 shows a typical result of corrected NOx measurement (15% O_2) as a function of equivalence ratio for combustor with- and without-TVC. NOx emissions are lower for a combustor with the TVC when the flame exists in the trap cavity at higher equivalence ratios. This may be due to lower mixture temperature in the TVC caused by heat transfer to the wall of TVC while residing in the TVC. The TVC has a

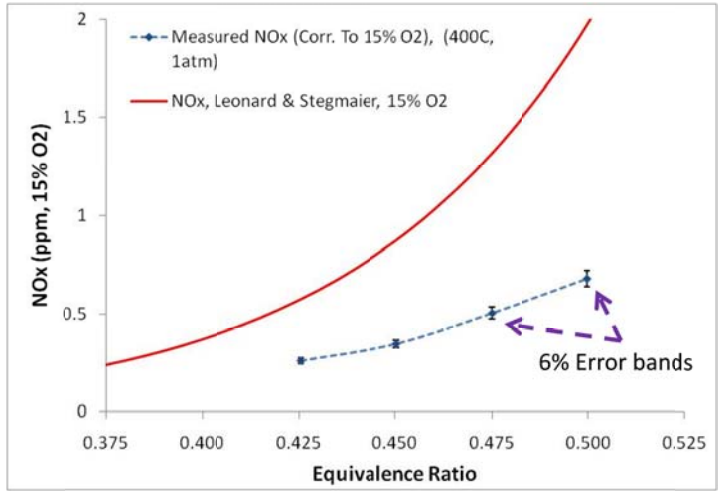

Figure 15: Corrected NOx (15% O_2) as a function of Equivalence Ratio for Combustor without TVC

relatively high surface area-to-volume ratio. As the flame is pushed into the combustor at the lower equivalence ratio (~ 0.43), the NOx emission becomes the same as for combustor without TVC. This is because the combustion products do not reside in the TVC anymore.

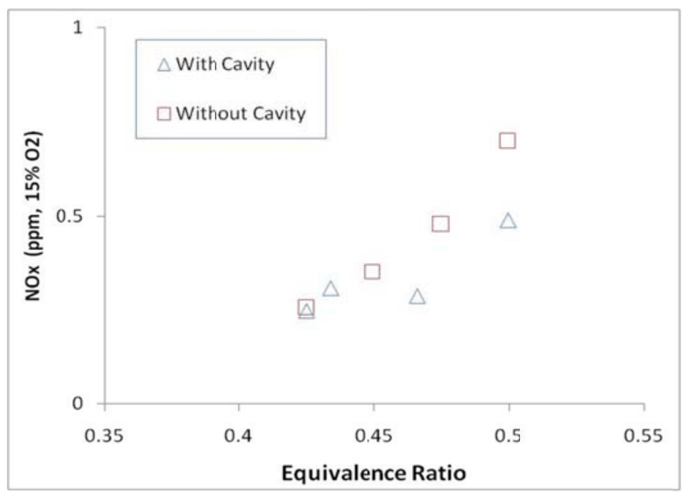

Figure 16: Actual (corrected for 15% O_2) NOx as a Function of Equivalence Ratio for Combustor With and Without TVC for U_{mean}=30 m/sec and Vane Thickness of 29.86 mm

CONCLUSIONS

A scaled, modular rig that models a commercial 250 kilowatt microturbine combustor was designed and fabricated to determine the feasibility of a novel combustor concept ('g-load' combustion) to extend the lean-blowout (LBO) limit.

CFD analyses of the test rig were performed to calculate g-load and flow field in the rig combustor at various flow conditions for the fabricated test rig. It confirmed that a wide range of g-loads (770-5050) could be achieved with the designed test rig. The CFD was also used to estimate the residence time of the flows inside the trap cavity.

Maps of flame regime were identified over the range of operating conditions. It was found that the flame resides in the trapped-vortex cavity when the equivalence ratio is within a certain range near the lean blow out (LBO) limits. The existence of TVC extends the LBO limit to lower equivalence ratio for all cases up to 5% when compared with cases without TVC. The LBO limits were found to be narrowed as the g-loads increased, indicating the increase of turbulent velocity with respect to g-load as found in Lewis is not the reason for the extension of LBO limits when the TVC is used as a part of the combustor. Also, it was found that the LBO limits decrease as the residence time increases for all vanes, suggesting the improvement of LBO limits is mainly due to the increase of residence time of mixture in the TVC.

The residence times of this study were based on CFD simulations. Detailed measurements of the actual exchange of reactants into and products out of the TVC are recommended for future investigations, especially as related to the g-load within the trap cavity.

Actual NOx emission measurement results show that NOx concentration does not change more than 6% of the mean value as the mean velocity is varied from 20 to 30 m/sec.

Based on the investigation results, the effect of g-load on the flame regime was identified. The novel combustor design concept which used a trapped vortex chamber extended the lean blowout limits to marginally lower levels (5%). This will enable operation at lower equivalence ratios, reducing the NOx emissions. It showed that when the flame regime includes combustion in the trapped vortex cavity, NOx is reduced compared to the baseline combustion concept.

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