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The Effect of Centerbody Geometry on Lean Blowoff in a Swirl-Stabilized Flame

Christopher Birkbeck, Ian Rivera, Cristopher Torres, Javier Rodriquez Camacho, Jacqueline O'Connor

Mechanical Engineering, The Pennsylvania State University, University Park, PA, USA
cdb5594@psu.edu

Abstract: Lean premixed (LP) combustion systems are currently used for most modern power generation gas turbines. Though this method reduces emissions, specifically nitrogen oxides, and is more efficient than non-premixed systems, LP systems are susceptible to blowoff. The goal of this study is to find out how centerbody geometry plays a role in the lean blowoff process for swirl-stabilized flames. We find that cylindrical centerbodies have higher lean blowoff equivalence ratios than tapered centerbodies. We also find that the dominant flame shape for both centerbodies is M-shape when not anchored and tulip shaped when anchored, though the tapered centerbodies induce V-shape flames as well. The blowoff equivalence ratio and blowoff process are strongly coupled ith the flame shape.
Keywords: swirl-stabilized flame, blowoff, centerbody

1. Introduction

Modern power generation gas turbines typically use a lean premixed combustion method that results in low emissions. Consequently, the lean mixture tends to create a weaker flame that is more susceptible to combustion instabilities [1]. To help anchor the flame, a variety of flame stabilization techniques are used, including swirling flow and centerbody stabilization [2]. The recirculation generated by both the swirling flow with vortex breakdown and the centerbody helps to keep the flame in the combustor, even at lean equivalence ratios [3].

Despite this advanced combustor design, lean blowoff, where the flame detaches from its stabilization point, can still occur in these systems [4]. This study considers the effect of centerbody geometry and swirl number on lean blowoff. Lean blowoff is characterized here by the critical equivalence ratio, which is the equivalence ratio at blowoff. The centerbody shape can significantly change the flow structure and hence the flame shape [5], thereby potentially affecting blowoff. In this study, we consider both the shape and location of the centerbody and the impact these have on the blowoff equivalence ratio and blowoff process.

2. Methods / Experimental

The testing was done in a swirl rig shown in Figure 1. The combustor uses a radial-entry, variable-angle swirler, which can be set from -70 to +70 degrees, resulting in swirl numbers up to 2.14. The swirler was set to +55 degrees for the testing in this study, resulting in a geometric swirl number of 0.97 for tapered centerbodies and 1.11 for cylindrical centerbodies. The centerbody is attached to the swirler, which extends from the swirler to the dump plane. Two centerbody shapes are considered: a cylindrical and tapered geometry. The diameters of the two centerbodies at their downstream end are 0.5 inches for the cylindrical and 0.13 inches for the tapered. The location of the centerbody relative to the dump plane is also varied. The first configuration has a centerbody that is flush with the dump plane and the second has a centerbody that is recessed below the dump plane by 0.699 or 0.298 inches. The centerbody is located in the nozzle that has a diameter of 1 inch. The combustion chamber is made of a cylindrical quartz tube with a diameter of 5.25 inches.

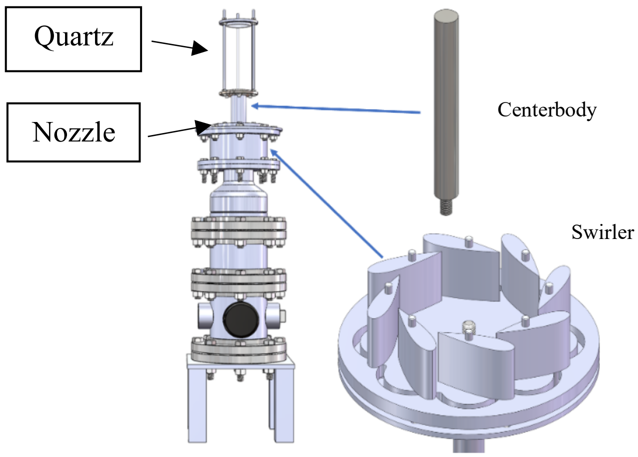


Figure 1. Experimental Swirl Rig, Centerbody, and Swirler

The quartz is held in place between a circular top flange and the dump plane.
The data acquisition included two pressure transducers and a photomultiplier tube (PMT). The pressure transducers were used to capture pressure fluctuations in the rig and were both placed in the injector nozzle where the centerbody is located. The PMT was used to collect CH* and OH* chemiluminescence signals with filters at 430 nm and 308 nm, respectively; both filters had a width of ±10 nm.

This data was taken during the blowoff process. First, the experiment was lit and brought to an equivalence ratio of 0.8. The flame was run until thermal equilibrium was achieved. Then, the equivalence ratio is reduced at a constant rate until blowoff is achieved. For data recording, we took twenty seconds of blowoff data where there were 200,000 samples taken with 10,000 samples/s for the PMT and pressure transducer data for each run. When taking blowoff data, we recorded approximately three seconds of steady-state data before starting the blowoff process. Videos were also taken throughout the whole flame cycle (steady-state and blowoff) for each run.

3. Results and Discussions

The testing consisted of seven different bulk velocities and five different centerbodies at one swirl number at a blade angle of 55 degrees. The bulk velocity was varied from 25 to 55 m/s in steps of 5 m/s with each velocity having three runs conducted for all the centerbodies to ensure repeatability. The steady state flame shape differed for the different centerbodies. As can be seen in Figure 2, the cylindrical center bodies had more of an M-shape flame, whereas the tapered center bodies had an M-shape and V-shape (Figure 3) flame as well. The M-shape is more defined for the cylindrical centerbody, where in the flame is present in the outer shear layer. A tulip flame in Figure 4 can be seen for both centerbodies when they are flushed with the dump plane for all velocities.

Figure 2. M-Shape

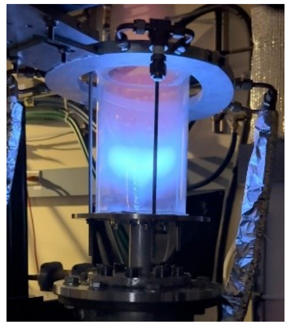


Figure 3. V-Shape

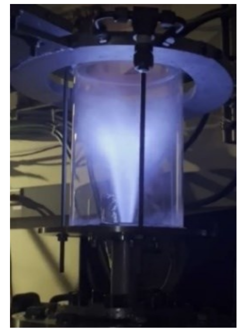


Figure 4. Tulip-Shape

Figure 5 and Figure 6 show the blowoff equivalence ratio as a function of flow velocity for two centerbody shapes (tapered and cylindrical) and the flushed geometries (Figure 5) and the recessed geometries (Figure 6), the cylindrical centerbody for both flush and recessed cases have higher lean blowoff equivalence ratio than the tapered centerbodies. There are two recessed cylindrical centerbodies: CB1 is recessed by 0.298 inches and CB6 is recessed by 0.699 inches. There are three comparisons to make in this data. First, Figure 5 shows comparisons between a cylindrical (CB1) and tapered (CB4) centerbodies at the flushed conditions. Here, there is not much of a difference between the blowoff equivalence ratios until the very highest velocity. This difference could be by the flame shape, where the V-shape flame on the tapered centerbody.

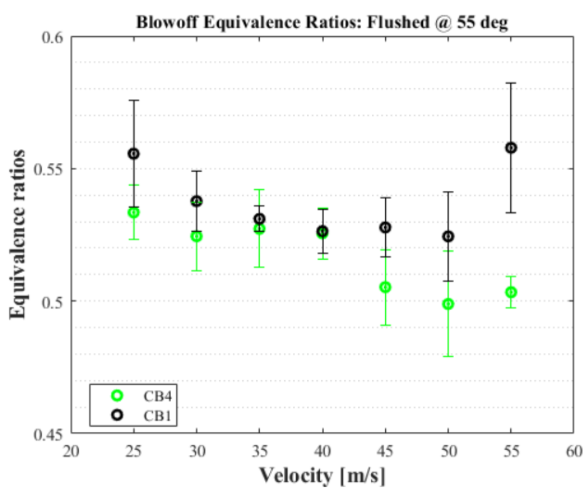


Figure 5. CB4 is Tapered & CB1 is Cylindrical

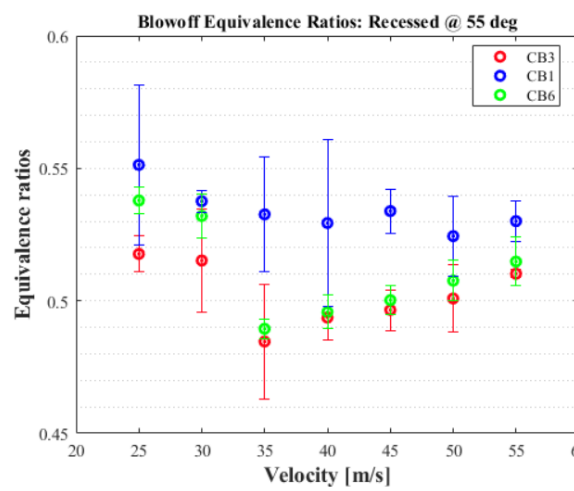
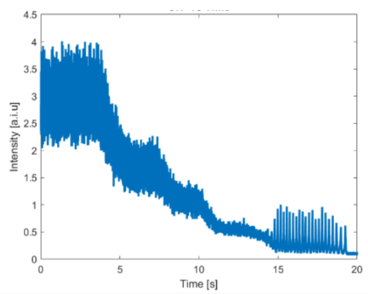


Figure 6. CB3 is Tapered & CB1 & CB6 are Cylindrical

Second, one can compare the flushed (Figure 5) and recessed (Figure 6) cases where the M-shape dominates for higher velocities and the tulip shape for lower velocities. Overall, the blowoff equivalence ratios are lower for the recessed cases than the flushed cases. Further, there is a difference in the level of recess. Both CB3 and CB6 are recessed by 0.699 inches, whereas CB1 in Figure 6 is recessed by significantly less, 0.298 inches. Over a large range of velocities, the cases with a large recess (0.699 inches) for both centerbodies have lower blowoff equivalence ratio.

The differences in flame shape also drive differences in the blowoff process. Figures 7 and 8 show the CH* signals with time for two different blowoff patterns. In Figure 7, the blowoff process ends in flame chugging, where chugging is the rapid ignition and extinction of the flame. In Figure 8, the blowoff process ends in a tulip flame before the flame completely blows out all at once. For CB1, every run ended in chugging. For the rest of the cases, the blowoff process was dependent on the velocity. In general, flames from 35 to 55 m/s experienced chugging. However, a tulip flame was seen at higher velocities.



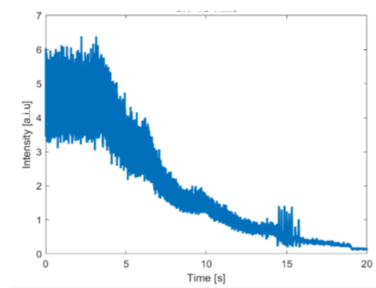


Figure 7. CH* ending in chugging   Figure 8. CH* ending with a tulip flame

4. Conclusions

This study investigated the effect that centerbody geometry has on lean blowoff equivalence ratio. We found cylindrical centerbodies generally have a higher lean blowoff equivalence ratio than tapered centerbodies, particularly at high velocities. It was also observed that cylindrical centerbodies more often have an M-shape flame, while tapered had a mixture of both M-shape and V-shape flame. In addition, a tulip flame can be seen for both centerbodies for the lower velocities, where the flame is anchored on the centerbody. Another finding is that the equivalence ratio is higher if the blowoff process ends in chugging than if it ends with a tulip flame, where lower velocities tend to end blowoff with chugging.

5. Acknowledgements

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6. References

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