Sub Topic: IC Engines, Gas Turbines, and Rockets

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Effect of Centerbody Temperature on Blowoff Limits of a Swirl-Stabilized Flame

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Abstract: Swirl-stabilized flames are used in many gas turbine combustor configurations due to their enhanced static stability. The effects of combustor geometry, fuel composition, and bulk velocity on flame stability in swirling flows are well studied, but the effects of centerbody temperature have not been rigorously considered. The purpose of this study is to understand the impact of centerbody temperature on flame shape and dynamics. A newly instrumented variable-angle swirl-stabilized combustor was used to perform a repeatability study, and blowoff equivalence ratio was measured at centerbody temperatures ranging from 150 to 350°C and bulk velocities ranging from 16 to 55 m/s. Blowoff equivalence ratio generally decreases with centerbody temperature. Two structures were observed during blowoff: a cone shape and flame chugging. Blowoff equivalence ratio was consistently lower when the cone structure occurred, though the mechanism that excites these behaviors is still under investigation.
Keywords: Swirl-Stabilized Flames, Lean Blowoff Dynamics.

1. Introduction

Lean combustion improves engine efficiency and lowers the flame temperature, reducing NO_x emissions. However, instabilities are introduced because lean flames are more sensitive to external perturbations. To enhance flame stability, the fuel-air mixture is passed through vanes that swirl the flow before it enters the combustion chamber through an annular opening. The introduction of swirl causes recirculation zones that extend the residence time of fuel-air mixing in the combustion chamber and gives the fuel sufficient burn time [1–2]. This flow structure stabilizes the flame, anchoring it to the centerbody (CB). Swirl-stabilized flames are used in a range of gas turbine combustor configurations because of the enhanced static stability provided by swirling flows [3].

Combustor geometry, fuel composition, and air speed (u_{bulk}) all affect flame stability in combustors. Stability is often quantified using the critical equivalence ratio (ϕ_{critical}), which is the equivalence ratio at which the critical event occurs. When u_{bulk} is too low, the flame enters the mixing area causing flashback, but when u_{bulk} is too high, it cannot stay anchored and experiences blowoff [4]. In this study, we consider the impact of CB temperature (T_{CB}) on the blowoff limits of a swirl-stabilized flame. Blowoff has been attributed to the cooling of the inner recirculation zone (IRZ) via a few different mechanisms: 1) cold backflow in the downstream region, 2) leakage of cold, unburned mixture through local extinctions in the shear later, and 3) local extinction at the flame root, weakening its attachment to the CB [5]. These blowoff mechanisms suggest that a higher temperature at the flame root will increase stability. Recently, Wang et al. showed that flame stability increases with a higher bluff body temperature for lean, premixed DME/air flames [6]. This result is consistent with our previous work that suggests a stability dependence on T_{CB} in methane flames. As such, the goal of this work is to better understand the impact of T_{CB} on ϕ_{blowoff} and its qualitative process in swirl-stabilized flames.

2. Experimental Methods and Data Analysis

The experiment shown in Figure 1 is a swirl-stabilized combustor. Premixed fuel and air enter the stagnation chamber and are passed through perforated plates and constriction to ensure that the flow is uniform as it passes through the 65-degree swirler. Swirling premixed fuel and air passes through a 1" diameter nozzle to the combustion chamber where the flow field is studied. A thermocouple is embedded in the CB to measure its temperature throughout blowoff.

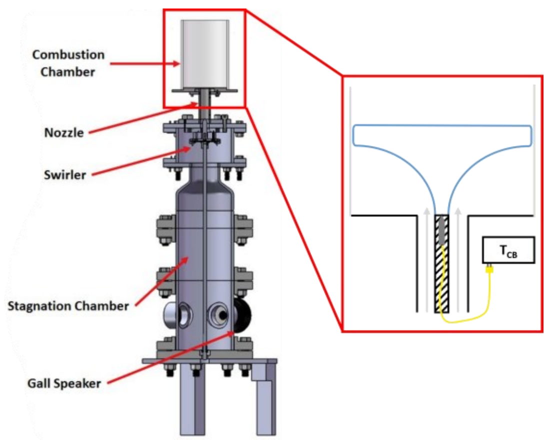

Figure 1. Cutaway schematic of the swirl rig combustor to show the swirler location, CB thermocouple, and flow path.

Blowoff limits were determined with a repeatable experimental procedure. During each test, fuel and air flowrates were increased to an initial equivalence ratio, ϕ_0 = 0.8. Once T_{CB} reached the target, data acquisition was started simultaneously with the reduction of fuel flowrate until blowoff, and ϕ_{blowoff} was recorded. To ensure that the variability of this transient process did not affect repeatability, we tested the condition at u_{bulk} = 23 m/s nine times. As shown in Figure 2, T_{CB} changes in a highly repeatable manner. Similar tests were done for u_{bulk} ranging from 16 to 55 m/s. and every condition except 16 m/s was shown to be repeatable.

CH* chemiluminescence and T_{CB} were measured through the blowoff process to track flame intensity and centerbody temperature profile, respectively, and qualitative observations of flame shape and blowoff process were recorded after each test. Each test was repeated at least three times to demonstrate that the results could be reproduced reliably. The data were analyzed in several ways. Blowoff equivalence ratio was plotted against u_{bulk} and T_{CB} to track trends. High-speed flame visualization was used to interpret some of the results. Qualitative flame shape observations were correlated with CH* measurements and categorized by flame structure.

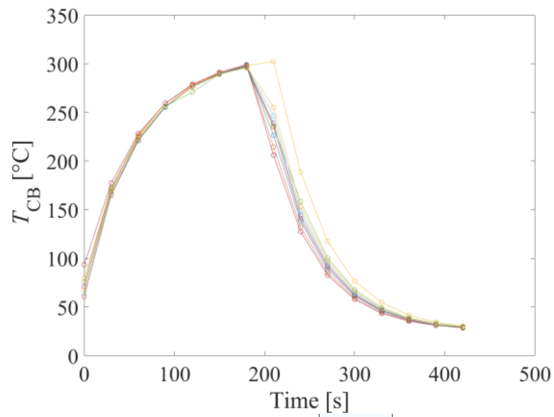

Figure 2. Repeatability study (n = 9) for u_{bulk} = 23 m/s.

Commented [CC1]: Does this work to represent that there are 9 runs reflected in this graph?

Commented [TC2R1]: I was going to suggest explicitly saying "Nine Test Runs" but since you already mentioned the 9 runs in the text I think this should be fine

Commented [MC3R1]: I agree. I think what's written is explicit enough.

3. Results and Discussion

3.1. Test Matrix

Table 1 shows the test matrix considered in this study, where white blocks indicate test points, black blocks indicate test points that were not achievable. This study was run for several flow conditions with bulk velocities ranging from 16 to 55 m/s. The blowoff process was initiated at multiple T_{CB} in increments of 50°C ranging from 150 to 250°C, 150 to 300°C, and 200 to 350°C for velocities of 16 m/s, 20 to 35 m/s, and 39 to 55 m/s, respectively.

Commented [CC4]: Instead of discuss gray squares, I modified the table to reflect this sentence. That should cover all the bases.

Commented [TC5R4]: Agreed, I think this is probably the best way we can represent our test matrix

Commented [MC6R4]: Same. Matrix looks good and is clear for what was discussed.

Table 1. Test matrix with variations in bulk flow velocity and initial centerbody temperature.

T_{CB} [°C] / u_{bulk} [m/s]	150	200	250	300	350
16					
20					
…					
35					
39					
…					
55					

3.2. Blowoff Equivalence Ratio and Centerbody Temperature

The effects of T_{CB} and u_{bulk} on $\phi_{blowoff}$ for a swirl-stabilized flame are shown in Figure 3 and Figure 4, respectively. There is weak inverse relationship between T_{CB} and $\phi_{blowoff}$, meaning that flame stability generally increases with increasing T_{CB} across a range of operating conditions. This result was expected because blowoff can be induced by cooling in the IRZ [4]. Maintaining a higher temperature near the flame's root likely reduces cooling effects and improves overall stability.

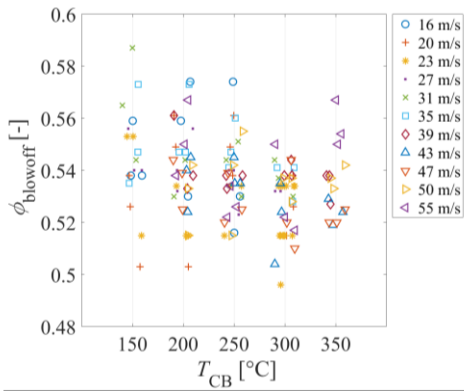

Figure 3. $\phi_{blowoff}$ plotted against T_{CB}.

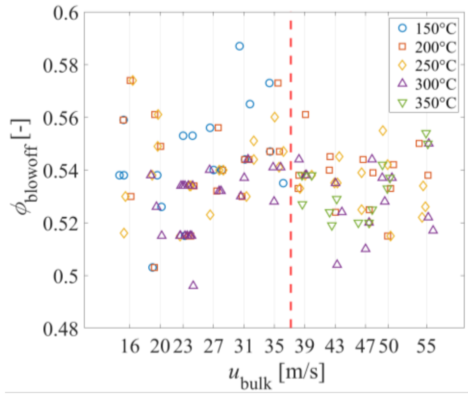

Figure 4. $\phi_{blowoff}$ plotted against u_{bulk}.

In the low-speed regime, between 20 and 35 m/s, $\phi_{blowoff}$ increases as u_{bulk} increases, which is consistent with prior results [7]. However, between u_{bulk} = 39 and 47 m/s, $\phi_{blowoff}$ decreases. High-speed flame visualization was used to track the flame geometry in these two regimes. As shown in Figure 5, the flame stabilizes in the inner shear layer in the low-speed regime, forming a “V” flame. But in the high-speed regime, the flame extends to the dump plane and stabilizes in the outer shear layer, forming an “M” flame. It is believed that this change in flame geometry is responsible for the increased flame stability in the high-speed regime. Further imaging of flame processes between these two conditions is necessary to better understand the differences in blowoff mechanism.

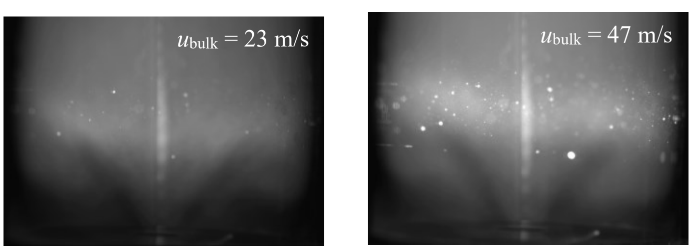

Figure 5. High-speed flame visualization. Left: u_{bulk} = 23 m/s. Right: u_{bulk} = 47 m/s.

3.3. Flame Behavior During Blowoff

The flame displays two possible behaviors during blowoff: a cone shape and flame chugging, as depicted in the photographs in Figure 6. Categorizing the data in Figure 3 reveals that the cone shape is generally more stable than cases with flame chugging, as shown in Figure 7. This result is likely because flame chugging allows the base of the flame to cool more rapidly than the cone, which remains attached. The mechanism that excites these behaviors is unclear. Further variable categorization and analysis might explain these flame structures during blowoff.

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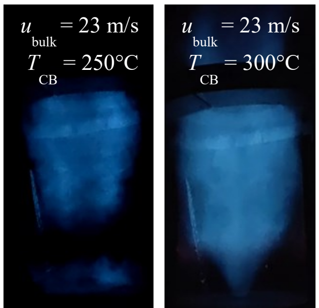

Figure 6. Flame behaviors during blowoff. Left: Chugging. Right: Cone.

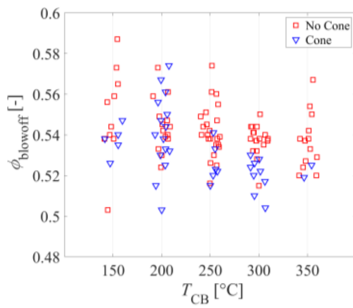

Figure 7. $\phi_{blowoff}$ plotted against T_{CB}, categorized for blowoff flame behavior.

4. Conclusions

Controlling combustor centerbody temperature results in repeatably lower blowoff equivalence ratios for swirling flames. Controlling T_{CB} can be used in modern combustor configurations to improve flame stability during lean operating conditions. High-speed flame visualization suggests that the observed increase in flame stability at higher bulk velocities is caused by fundamentally different flame shapes in low- and high-speed regimes for this variable-angle swirl combustor. Two exclusive flame structures were observed during the blowoff process: cone and chugging. While the mechanism behind these flame shapes is unclear, the cone consistently had a lower blowoff equivalent ratio and a smaller data spread than chugging. Further chemiluminescence testing and analysis should clarify the cause of the different blowoff behaviors.

5. Acknowledgements

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6. References

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Commented [CC7]: Is it worth commenting that these are cell phone images? Since we mentioned that we used CH* to confirm the chugging/cone behavior, I wanted to show those graphs for both cases, but I don't think there is space, unfortunately.

Commented [TC8R7]: I think this should be fine, unless you think the reader may be confused, I would just leave the images as is.
I agree having the CH* graph like in Ian's would have been cool to include with more space, but I think the chugging vs cone images do a good job representing this.

Commented [MC9R7]: I think you could briefly mention the images included are regular photographs, not necessarily that they were taken with a cell phone to clarify that those images are not the CH* data.