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Swirl number effects on the blowoff limits of swirl-stabilized flames

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Abstract: This work focused on understanding how swirl influences the blowoff limit and process in lean-premixed, swirl-stabilized flames. Two initial equivalence ratios (Φ_0 = 0.8 and 1.0) were used to study the effect of swirl number (S = 0.80, 0.95, 1.15, and 1.43) on the lean blowoff limits. It was seen that at higher Φ_0, the blowoff equivalence ratio of flames with lower swirl levels was typically more sensitive to bulk flow velocities than flames stabilized at lower Φ_0. The blowoff Φ of flames stabilized at higher swirl levels did not vary much with an increase in bulk flow velocity. Global CH* chemiluminescence was done to study the lean blowoff process further. At lower Φ_0 and swirl levels, the occurrence of the extinction/reignition events in the shear layers seemed more prominent.
Keywords: Swirling flames, Blowoff limits, Flame stability

1. Introduction

Lean premixed combustion can result in unsteady combustion phenomena that give rise to flow velocity and equivalence ratio fluctuations [1], which can lead to flame blowoff. Blowoff is the sudden extinction of the flame in the combustor and its onset requires a potentially damaging restart of the engine. Generally, blowoff occurs if the velocity of the incoming flow is too high and the flame cannot find a location where the kinematic condition is met. While swirl helps stabilize lean premixed flames by establishing low-velocity regions and recirculation zones [2], swirl-stabilized flames can still be prone to blowoff at very lean conditions. Radhakrishnan et al. [3] related the bulk flow velocity to the blowoff equivalence ratio and stated that these two parameters are directly proportional. Additionally, changes in blowoff behavior with turbulence are directly related to changes in flame structure [4]. Huang and Yang [5] studied the impact of swirl in the flame dynamics of a lean-premixed, stabilized combustor and showed that swirl number variations can lead to differences in flow structure and turbulent flame speed. Durox et al. [6] found that as the swirl number changes, the flame shape changes due to changes in the axial velocity profile and the size of the recirculation zone. Given the strong connection between swirl number and flame stabilization, this work utilizes a unique variable-angle swirling facility to explore the effects of swirl on CH_4/air lean blowoff limits.

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2. Methods / Experimental Rig

Experiments were conducted on a variable-angle swirl rig with a cylindrical centerbody, as shown in Figure 1. The swirler contains eight evenly spaced NACA 0025 airfoils that are 1" tall and 1" in cord length. This swirler dramatically changes the flow field as the blade angle changes within a range of -70º to 70º. In this study, the swirl numbers used to examine how swirl influenced the static stability of the flame were 0.80, 0.95, 1.15, and 1.43, calculated using the geometric swirl number [7]. A cylindrical bluff body with a 0.5" diameter is located downstream of the swirler and in the 1" diameter nozzle of the combustor rig. The end of the centerbody is leveled with the dump plane of the combustor.

Piezoelectric dynamic pressure transducers are placed in the annular nozzle passage at 2.72" and 0.724" upstream of the nozzle exit to record pressure fluctuations. Photomultiplier tubes (PMTs) were used to record global chemiluminescence of CH*, evaluating the heat release rate fluctuations in the flames. More details of the experimental rig were discussed in Mason et al. [8].

A repeatable experimental procedure was developed for the measurement of blowoff limits. Air and fuel flow rates were calculated and adjusted in the combustor until initial equivalence ratios of Φ_0 = 0.8 and 1.0 were reached. These equivalence ratios were used for different tests to evaluate the impact Φ_0 could have on blowoff. After the desired equivalence ratio was reached, the bluff body was allowed to reach a target temperature to maintain a constant centerbody temperature and limit the effects it can have on blowoff. To obtain the blowoff limits, we steadily decreased the fuel flow rate and recorded the equivalence ratio when the flame extinguished completely. We waited several minutes between tests so that the bluff body temperature could return to a baseline level and limit variability.

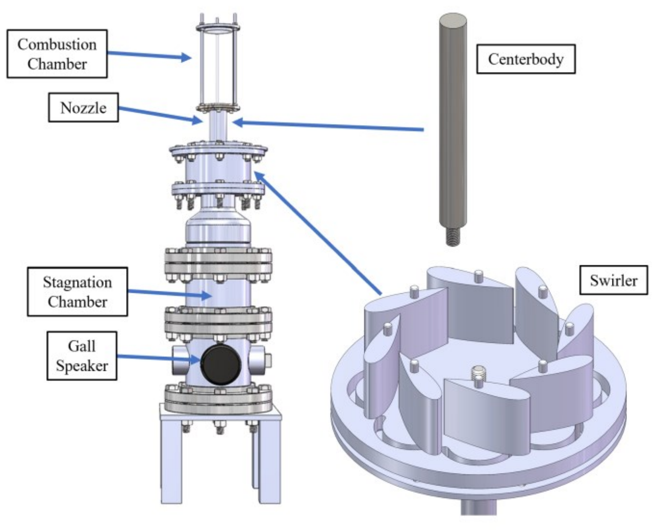

Figure 1. Schematic of variable swirl-angle rig used. The centerbody is located inside the nozzle.

3. Results and Discussion

To establish repeatability and assure accurate results, 10 tests at u_{bulk} = 25 m/s and Φ_0 = 0.8 were done. The blowoff equivalence ratios of 0.50-0.54 were measured with a standard deviation of 0.0137. Figure 2 shows all the data collected in this study. We tested each velocity at least three times to improve accuracy. Points in this graph represent the medians of all the tests completed and the error bars represent the interquartile ranges for each velocity and equivalence ratio case. The results in Figure 2 show two different trends. First, flames stabilized at a lower swirl number have blowoff equivalence ratios that are generally more sensitive to bulk flow velocity than the higher swirl number case. For example, the *S*=1.43 (green circles) cases are relatively insensitive to bulk flow velocity, whereas most of the cases with the lower swirl numbers (0.80-1.15) show an increase in blowoff equivalence ratio with increasing velocity, as is expected. Second, the initial equivalence ratio of the test has an impact on the blowoff behaviors. Higher initial equivalence ratio cases are seen to be more sensitive to bulk flow velocities and blow out at higher equivalence ratios. For example, S = 0.95 cases at Φ_0 = 1.0 (black stars) blow out at blowoff Φ from 0.575-0.672, while cases at Φ_0 = 0.8 maintain an almost steady blowoff equivalence ratio of around 0.538.

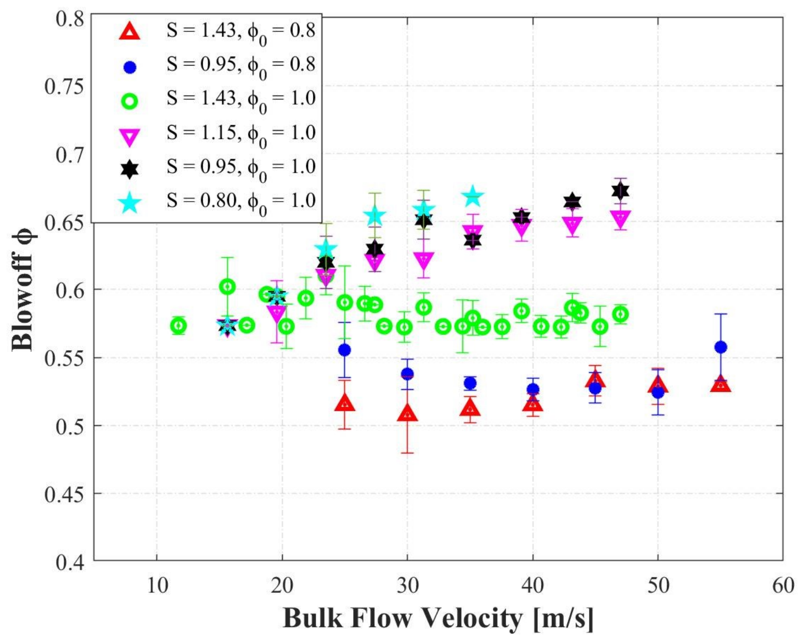

Figure 2. Blowoff equivalence ratio as a function of bulk flow velocity for several swirl numbers.

The trends between the two different swirl cases S = 0.95 and S = 1.43 at Φ_0 = 0.8 can be further studied with heat release rate data, as shown in Figure 3. CH* global chemiluminescence reveals sudden peaks in heat release rate when approaching blowoff due to extinction/reignition events, or chugging in the shear layers, as previously seen by Chaudhuri et al. [9]. Lower swirl numbers are shown to result in higher occurrences of chugging, possibly due to the reignition of fresh reactants entrained in the recirculation zone the flame. Further flame and flow imaging is necessary to understand the impact of recirculation zone size and position on these reignition events and the blowoff process.

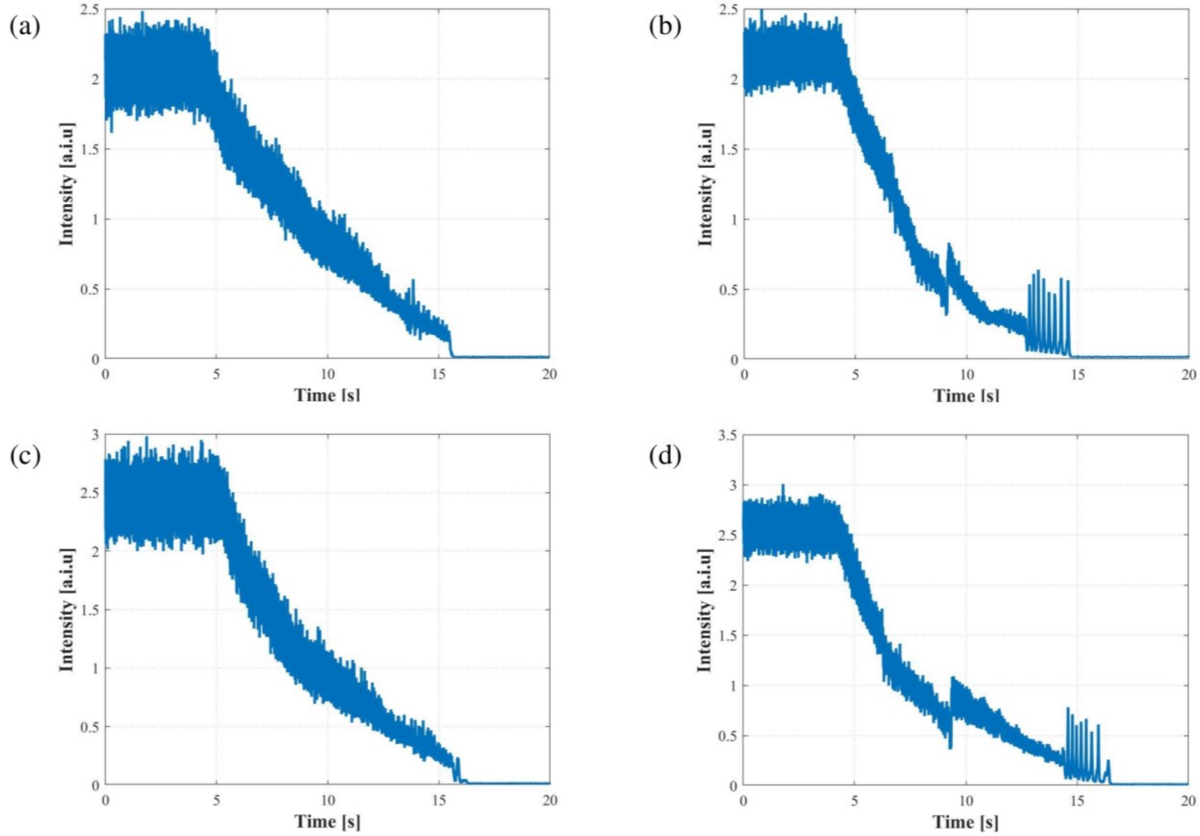

Figure 3. Global chemiluminescence of CH* showing heat release rates. Peaks in these graphs demonstrate change in flame shape and extinction/reignition when approaching blowoff: (a) 35 m/s, $S = 1.43$; (b) 35 m/s, $S = 0.95$; (c) 40 m/s, $S = 1.43$; (d) 40 m/s, $S = 0.95$.

4. Conclusions

This work considers the effects of swirl number on the blowoff limit and process in lean premixed combustion. It was found that Φ_0 heavily impacts how swirl levels affect the blowoff process. At higher Φ_0, flames stabilized at lower swirl levels are typically more sensitive to bulk flow velocities – blowoff Φ increases as bulk flow velocity increases. At lower Φ_0, flames stabilized at lower swirl levels generally show almost no sensitivity to these bulk flow velocities. Flames stabilized at higher swirl levels in both Φ_0 cases show an almost steady blowoff Φ as the bulk flow velocity increases. CH* global chemiluminescence was also used to study the hat release rates in the blowoff process. The occurrence of chugging seems more prominent at lower swirl numbers at $\Phi_0 = 0.8$. More data and diagnostics will be obtained to theorize the reason for this occurrence correctly. Still, the authors theorize that the size and position of the recirculation zone might impact the blowoff process and, thus, the lean limits of the combustor. Future work will include further testing and diagnostics to study the time-averaged flame shape and flow fields, giving the authors more insight into the impact of swirl in the blowoff process. Additionally, the authors will consider the impacts of acoustic forcing on the blowoff limits and process in these lean-premixed, stabilized flames.

5. Acknowledgements
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6. References

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