STUDIES OF LEAN BLOWOUT IN A STEP SWIRL COMBUSTOR

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ABSTRACT

The design requirements of a modern gas turbine combustor are increasingly dictated by wide stability limits, short flame length, and uniform mixing. To achieve the best trade-off between the above three factors, flame characteristics (length, shape, mixedness), lean blowout (LBO), and optimum combustor configuration should be investigated over a wide range of inner and outer air velocities, inner and outer vane angles, and co- vs. counter-swirl arrangements. Such an investigation was performed in a step swirl combustor (SSC) designed to simulate the fuel-air mixing pattern in a gas turbine combustor dome fitted with an airblast atomizer.

It was found that an increase in the outer vane angle and a decrease in inner air velocity decreased the flame length. LBO was improved when outer flow swirl intensity was increased. An optimum hardware and velocity configuration for the SSC was found for inner swirl = 45°, outer swirl = 60°, co-swirl direction, and inner air velocity = outer air velocity = 16 m/s. This optimum SSC configuration yielded: (i) low values of LBO, (ii) short flame length, (iii) uniformly mixed stable flame, and (iv) little or no variation in these characteristics over the range of operation of SSC. Finally, the co- vs. counter-swirl arrangements and the operation of the optimized combustor configuration were discussed.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>D</td>
<td>inner air nozzle diameter</td>
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<tr>
<td>LBO</td>
<td>lean blowout</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
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<tr>
<td>U</td>
<td>axial mean velocity</td>
</tr>
<tr>
<td>Y, Z</td>
<td>radial and axial distance, respectively</td>
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<tr>
<td>$\phi$</td>
<td>equivalence ratio</td>
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<tr>
<td>$\theta$</td>
<td>swirl vane angle</td>
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Subscripts

- i = inner
- o = outer

INTRODUCTION

An important design requirement of a modern gas turbine combustor is good combustion stability; that is, the combustor should sustain burning over a wide range of fuel-air ratios encompassing the entire range of engine operating conditions, including rapid acceleration and deceleration. Also, short flame length and uniform mixing are equally important. To achieve the best trade-off between wide stability limits, short flame length, and uniform mixing, the characteristics of the flame, lean blowout (LBO), optimum combustor geometry, and their influence on LBO should be investigated. This provides the necessary impetus for our research.

In this paper, experimental studies in a step swirl combustor (SSC) burning gaseous propane fuel were performed. The fuel was injected in the form of an annular jet coaxially sandwiched between two swirling airstreams. This configuration simulates the fuel-air mixing pattern just downstream of an airblast atomizer located in the dome region of a modern annular gas turbine combustor. The SSC was also intended to be a marriage between the two combustor configurations extensively studied earlier in our laboratory: a step combustor (Sturgess et al., 1990; 1991) and a swirl combustor (Takahashi et al., 1990). Specifically, we have investigated, over a wide range of inlet conditions of velocity, swirl vane angles, and swirl directions (co-swirl vs. counter-swirl): (i) flame characteristics such as length, shape, and mixedness; (ii) LBO; and (iii) combustor flow field patterns. Special emphasis was given to assess the flame characteristics of co-swirl vs. counter-swirl arrangements. For example, counter-swirl may generate a strong shear layer but the opposed airstreams tend to nullify the swirling motion in the flow field. On the other hand, co-swirl generates a high tangential momentum but produces a weaker shear layer. The combustion process in the SSC was also optimized in terms of a short flame length, high level of mixedness, and low LBO. Such results are presented and their implications to practical combustor design are discussed.
EXPERIMENTAL WORK

The SSC

Fig. 1 shows a schematic diagram of the SSC which has 150- x 150-mm cross section with rounded corners, length of 754 mm, and a step height of 55 mm. The SSC provides a geometrically simple, optically accessible research combustor capable of reproducing the fuel-air mixing pattern downstream of the airblast atomizer located in the dome region of a modern annular combustor. The SSC also offers independent control over inner and outer airstreams so that velocities can be easily optimized. In a practical airblast atomizer, effective areas would have to be changed to perform similar optimization; this is time consuming and expensive. The SSC was mounted on a vertical combustion tunnel with a three-axis traversing mechanism described by Sturgess et al. (1990). Measurements of various flame and flow parameters were performed using different instruments, the principal one being a three-component Laser Doppler Anemometer (LDA).

Fuel was supplied to the combustor by the annular fuel tube (20 mm i.d. and 29 mm o.d.) which is coaxially sandwiched between two swirling airstreams; the inner air jet (20 mm dia.) and the outer annular air jet (29 mm i.d. and 40 mm o.d.). The combustor exit has a 45% blockage orifice plate on top which simulates the back pressure exerted by the dilution jets in a practical gas turbine combustor (see Sturgess et al. 1990). The SSC has quartz windows on all four sides to permit visual observations and laser diagnostics measurements. Optical access in the axial direction was about 250 mm from the burner tube exit; in the radial direction, it was about 30 mm (3-D LDA) and 70 mm (2-D LDA) from the centerline.

Stationary helical vane swirlers were located 25 mm upstream from the burner tube exit in each of the air passages. The inner swirler had six vanes with a central 1.4 mm dia. hole to prevent the flame from anchoring to the swirler. The outer swirler had 12 vanes. Inner swirler lengths are 25, 19, and 19 mm, respectively, for 30°, 45°, and 60° swirlers; outer swirler lengths are 32, 25, and 19 mm, respectively, for 30°, 45°, and 60° swirlers. The lengths and number of vanes were designed to insure that there was no straight-through airflow into the combustor. Practical combustors usually employ axial-flow-type swirler vanes. The swirler vanes are usually flat for ease of manufacturing. However, the flow does not follow the angle of the flat vane as accurately as it does the angle of the helical vane. The swirlers were precision-fabricated in a rapid prototype manufacturing process known as stereolithography. These swirlers performed satisfactorily at high temperatures in our combustor.

Instrumentation

Fig. 2 shows a custom-made three-component LDA system used for velocity measurements. This is a three-beam two-component (axial and radial) set using a 514.5 nm line of an 18W argon-ion laser with a component separation based on polarization. A two-beam third component (tangential) set uses a 488.0 nm line with separation by color. Since the third component is normal to the first and second components, the measurement volume had a quasi-spherical shape of 100 µm diameter and the calculated fringe spacing was 3.6 µm. The LDA system has Bragg cell frequency shifting (10 MHz for the first and second channels, and 30 MHz for the third channel) for measurements in recirculatory flows, 4-σ filtering software for spurious signals, (e., due to seed agglomeration), and a correction subroutine to account for the LDA signal-biasing effects in combusting flows. A fluidized-bed seeder was used to inject submicron-sized (0.1 gm) ZrO2 particles into each passage. Counter-type (TSI 1990C) signal processors and tailor-made coincidence circuit ensured valid data rate acquisition. All the LDA signals were processed using our custom-designed software which calculates intensity, shear stresses, higher moments (skewness and kurtosis), and pdfs. Typical LDA sampling rates exceeded 1 kHz for both isothermal and combusting flow measurements.
Fig. 2: Schematic of a custom-made three-component LDA system used for velocity measurements.

Error Analysis
Both the fuel flow and airflow were monitored by separate electronic flow control units to within 1% and 3%, respectively. The combined error produced an uncertainty of 1.5% in equivalence ratio. The primary source of error in LDA measurement is the statistical bias of the final measured velocity towards higher mass flux (velocity \times density) when number-weighted averages are used to calculate stationary statistics. Chen and Lightman (1985) and Glass and Bilger (1978) have discussed bias correction schemes. After allowing for this bias, we estimated that for the single-stream seeding and relatively high-sampling rates of our experiments, the uncertainty in the measurement of mean velocity was 1% and for rms velocity 5%. Near the flame front, where intermittency would be much higher, the uncertainty in rms velocity could be as high as 7%. The long-term repeatability of measurements was found to be within 5% for turbulence quantities.

Test Conditions
Table 1 lists the test matrix for the SSC experiments. All tests were performed at room temperature and atmospheric pressure using gaseous propane fuel to establish a baseline. It should be noted that advanced, near-stoichiometric combustors of the future will admit fuel into the primary zone in a prevaporized state, and therefore, may not require high air velocities (> 100 m/s) for liquid fuel atomization employed in conventional combustors. The SSC was operated to study flame characteristics, flow field, and LBO. Five variables were extensively tested: (i) inner air velocity, (ii) outer air velocity, (iii) inner vane angle, (iv) outer vane angle, and (v) co-swirl vs. counter-swirl. The SSC was operated over a wide range of equivalence ratios. LBO data were collected by maintaining a constant airflow rate, heating the combustor to a near steady-state temperature at stoichiometric fuel-air ratio, and then gradually decreasing the fuel flow rate until blowout occurred. This is a procedure similar to that adopted by Sturgess et al. (1991). The flame length was defined as the distance from the nozzle exit to the flame tip and measured by taking individual color snap-shots of the combustion process, enlarging these photographs, and then carefully plotting the luminous boundary of the flame front. These photographs also provided data for visually assessing the quality of mixing.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
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<tbody>
<tr>
<td>Inner vane angle, (\theta_i), degrees</td>
<td>30, 45, and 60</td>
</tr>
<tr>
<td>Outer vane angle, (\theta_o), degrees</td>
<td>30, 45, and 60</td>
</tr>
<tr>
<td>Vane configuration</td>
<td>co and counter-swirl</td>
</tr>
<tr>
<td>Inner air velocity, (U_i), m/s</td>
<td>16, 32, and 48</td>
</tr>
<tr>
<td>Re</td>
<td>20, 40, and 60 \times 10^3</td>
</tr>
<tr>
<td>Outer air velocity, (U_o), m/s</td>
<td>8 and 16</td>
</tr>
<tr>
<td>Re</td>
<td>14 and 28 \times 10^3</td>
</tr>
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</table>
(mixedness) within the combustion zone, e.g., for a constant fuel and airflow rate, a yellow or sooty flame indicates locally rich zones, which suggests poor mixing.

RESULTS
Flame Characteristics

Flame length measurements were performed because it directly governs the length of the combustor dome. The measurements were taken at stoichiometric equivalence ratios to establish a baseline. Long exposure photographs of the flame were taken with a 35-mm camera. Typical photographs are presented in Fig. 3a-c to illustrate how flame configuration (length, width, and shape) changes for no-swirl, inner swirl, and outer swirl conditions. As seen in Fig. 3a, for the no-swirl case, the flame is lifted and the combustion zone is located closer to the combustor exit. Introducing a mild swirl in the inner airflow (Fig. 3b) not only shortens the flame, but also causes it to bulge out and fill the combustor cross section. Finally, as shown in Fig. 3c, swirling the outer instead of the inner airflow produces an attached flame with a not-so-beneficial elongated combustion zone downstream.

Flame lengths were measured for many different SSC operating conditions; these are shown plotted in Figs. 4 through 6. It should be noted that for all cases except the no-swirl conditions, the flame was nearly attached to the nozzle exit (at stoichiometric values). Fig. 4 shows a substantial increase in flame length with a three-fold increase in inner air velocity (for a constant value of outer air velocity and constant $\phi = 1.0$) for all combinations of swirler angles. Clearly, this appears to be due to a direct decrease in the mixture residence time. Fig. 5 compares flame length with changes in outer airflow for a constant value of inner airflow. It is found that the flame length decreases, but only when the outer vane angle is $60^\circ$ or higher, i.e., only when the outer swirl intensity (both velocity and vane angle) is sufficiently high. Finally, Fig. 6 illustrates the variation of flame length with co- and counter-swirl conditions for a velocity combination $U_i = 48$ m/s and $U_o = 16$ m/s. For all combinations of inner and outer vane angles, co-swirl direction produced shorter flames. It was also found that for equal velocities of inner and outer airstreams, the flame was very short and there was no noticeable difference in flame length between co and counter-swirl conditions.

![Fig. 3: Photographs illustrating the flame structure for different swirl configurations: (a) no-swirl, $\theta_i = \theta_o = 0$, (b) inner swirl, $\theta_i = 45^\circ$, $\theta_o = 0$, and (c) outer swirl, $\theta_o = 30^\circ$, $\theta_i = 0$. Test conditions were at $\phi = 1.0$, $U_i = 16$ m/s and $U_o = 8$ m/s.](image-url)

![Flame Length (mm) vs. Vane Angle (inner/outer) (co-swirl)](chart-url)

**Fig. 4:** Variation of flame length with vane angle at two different values of inner air velocity ($U_o = 8$ m/s).

![Flame Length (mm) vs. Vane Angle (inner/outer) (co-swirl)](chart-url)

**Fig. 5:** Flame length as a function of vane angle and outer air velocity ($U_o = 8$ m/s).
To further assess the influence of swirl direction on the combustion process, Figs. 7a and 7b show the photographs of co- and counter-swirl flame structures respectively. Both flames rapidly spread outwards. However, the co-swirl flame (Fig. 7a) has a dimple-shape at the center and shows some yellowish streaks downstream (evidence of nonuniform mixing and diffusion-controlled combustion), whereas the counter-swirl flame (Fig. 7b) has a bulb-shape which fully confines the bluish (evidence of uniform, premixed) combustion process.

Since the co- vs. counter-swirl effects are of great interest in practical combustor design, LDA velocity measurements were made to confirm the above findings. Figs. 8a-c show the radial variation of mean axial velocity at three different locations downstream of the fuel nozzle. These LDA measurements were made by seeding the fuel flow. A comparison between Figs. 8a and 8b demonstrates the changes in flowfield due to combustion, while Figs. 8b and 8c illustrate the co- vs. counter-swirl effects.
Fig. 8a shows the inner recirculation zone which grows from a width of 0.25D (at Z/D = 0.35) to 0.45D (at Z/D = 2.25) in the cold flow. In the annular fuel tube region, which is sandwiched between the inner and outer airflow, the axial velocity component is positive and decreases rapidly from its inner mean value of 16 m/s to the outer mean value of 8 m/s. Finally, the velocity decays to a low, but still positive value (i.e., no outer recirculation zone at least for Y/D up to 1.5) as one moves radially outwards from the edge of the outer air tube to the combustor wall.

As seen in Fig. 8b, the heat release of combustion produces the acceleration of the axial velocity component and elongation of inner recirculation zone in the axial (downstream) direction. For example, at Z/D = 1, combustion has elongated (and hence decreased) the recirculation zone width by 30 percent; and downstream of this location, it has increased the maximum mean axial velocity by 50 percent in this Y/D range. This means that throughout the inner recirculation zone, velocity gradients have increased significantly, contributing to intense mixing and uniformity. These results are consistent with the dimple-shaped central flame structure observed in the photograph in Fig. 7a.

Fig. 8c illustrates the axial mean velocity profiles for counter-swirl direction. These results show no evidence of any inner recirculation zone. Moreover, in the annular gap corresponding to the fuel tube location, the velocity profile has a minimum. Presumably, this arises due to the flow velocity cancellation effect produced by the counter-rotating swirl. Also, the annular fuel jet is subjected to strong shearing action of counter-rotating braids along its inner and outer boundaries. As is evident in Fig. 7b, this shearing action produces a very thin annular film near the nozzle exit (Z/D up to 1) which supports an attached flame structure in the combustor.

It should be noted that, in our experiments, the co- and counter-swirl arrangement had identical overall pressure drop. Yet there is a difference in their mixing characteristics and, hence, in the flame structures. Thus, expressing the mixing quality only in terms of the overall pressure drop can be deceptive.

**LBO Observations**

LBO equivalence ratios were recorded for all the test conditions documented in Table 1. Rich blowout data was also collected to verify combustion stability of SSC for various parametric combinations. However, in Figs. 9 and 10, only LBO data are presented (repeatability to ±0.01) because of its great practical importance. These data may be put into proper perspective by noting that, for a perfectly mixed propane-air flame, the value of equivalence ratio at the lean flammability limit is 0.55.

Fig. 9 shows that an increase in outer swirl vane angle improves the stability of lean mixtures (i.e., LBO values decrease). An outer vane angle of 60° produces strong outer recirculation zones which keep the flame attached to the exit nozzles and stabilize the combustion process. Strong outer swirl produces locally fuel-rich zones by directing the outer airflow away from the fuel jet, thereby further assisting flame stability.

Fig. 10 shows LBO data for co- and counter-swirl. When inner air velocity is significantly higher than the outer air velocity, co-swirl provides more stable combustion and always yields slightly lower LBO values than the counter-swirl condition. This presumably occurs because, as shown in Fig. 7a, the co-swirl flow direction produces less-uniform mixing in the combustor than the counter-swirl flow direction. An imperfectly mixed diffusion flame blows out at a lower overall equivalence ratio because combustion is sustained in the locally rich mixture regions. This is good for stability but it should be recognized that the reactants are not uniformly mixed. Thus, there is an important trade-off to be considered when assessing burning characteristics of co- and counter-swirl flows. No detectable differences in LBO values were found for co- and counter-swirl flow conditions when inner and outer air velocities were equal.

**Optimum Configuration**

The preceding results on flame length and LBO suggest an optimum configuration of inner and outer velocities, inner and outer swirl vane angles, and co- vs. counter-swirl which yields: (i) low LBO values, (ii) short flame length, (iii) uniformly-mixed stable flame, and (iv) little or no variation in these characteristics over the SSC range of operation. Fig. 11 shows that the optimum vane angle (θi = 45°, θo = 60°) provides low LBO values (average equivalence ratio = 0.38 ± 0.04) and short flame lengths.
(average 55 mm ±10 mm) over the range of air velocities tested. For all other inner and outer vane angle combinations, the average LBO values were greater, average flames were longer, or more data variability was present. Likewise, in Fig. 12, the optimum inner and outer velocity split (\(U_i = U_o = 16\) m/s) provides low values of LBO (average equivalence ratio = 0.41 ± 0.03) and short flame length (average 52 mm ±8 mm) over the range of vane angles tested.

![Graph showing variation of LBO and flame length with airflow](image)

**Fig. 11:** Variation of LBO and flame length with airflow for an optimum vane angle configuration (\(\theta_i = 45^\circ, \theta_o = 60^\circ\)).

![Graph showing variation of LBO and flame length with vane angle](image)

**Fig. 12:** Variation of LBO and flame length with vane angle for an optimum air velocity split (\(U_i = U_o = 16\) m/s).

Figs. 13a and 13b show the flame structure at the optimum condition (inner swirl = 45°, outer swirl = 60°, co-swirl direction, inner air velocity = outer air velocity = 16m/s) for an equivalence ratio \(\phi = 1.0\) and 0.5, respectively. It is observed that the flame structure remains confined to the combustor dome region over this range of equivalence ratio. At the overall stoichiometric mixture ratio (Fig. 13a), the flame is evenly dispersed throughout the combustor and the same observation holds true at the LBO operating condition (Fig. 13b). While this may be aerodynamically desirable, other factors such as combustor dome cooling, high-altitude ignition, and emissions requirements can dictate the optimum flame structure in a practical combustor. Finally, no noticeable change was observed in flame size and shape when the inner swirl angle was increased from 45° to 60°.

![Images of flame structures](image)

**Fig. 13:** Photographs illustrating the flame structure at the optimum conditions (\(\theta_i = 45^\circ, \theta_o = 60^\circ, U_i = U_o = 16\) m/s), (a) \(\phi = 1.0\), (b) \(\phi = 0.5\).

**DISCUSSION**

In these experiments it was observed that, compared to the counter-swirling arrangement, the co-swirling flow spread the fuel-air mixture to the combustor walls and produced a slightly shorter flame, a lower LBO value, and less variability of the combustion characteristics with changes in hardware and flow conditions. For a co-swirl arrangement, Brady and Samuelsen (1991), Brady et al. (1991), and Sowa et al. (1993) have observed an excessive transport of liquid fuel to the combustor walls resulting in unstable operation. Since the momentum of their liquid fuel sheet was likely to be higher than that of our gaseous propane annular jet, their observations on combustor wall heating and combustion instability were absent in our tests. Also, as Sowa et al. (1993) have pointed out, shorter combustor dome length required to confine this type of flame may suppress the formation and strength of large-scale turbulent eddies which trigger combustion instabilities. As shown in Fig. 7a, we did observe some yellow streaks downstream; these streaks indicate nonuniform mixing and diffusion-controlled combustion. However, combustion instability for the co-swirl arrangement at the LBO operating point was no worse than with the counter-swirl flow arrangement.

Finally, detailed velocity and temperature mappings of the SSC using LDA and CARS diagnostics are currently being performed to ascertain the role of inner and outer recirculation zones on the combustion stability near lean blowout.
SUMMARY AND CONCLUSIONS

A unique SSC was designed to simulate the fuel-air mixing pattern produced by an airblast atomizer located in the combustor dome of a modern annular gas turbine combustor. Experiments were performed to study flame characteristics (length, shape, and mixedness), LBO, and flow patterns in this combustor over a wide range of inner and outer velocities, inner and outer vane angles, and co- vs. counter-swirl arrangements. This research resulted in the following findings:

1. The two most significant parameters that contributed to decreasing the flame length are: an increase in the outer vane angle and a decrease in inner air velocity. Visual flame sooting decreased when the inner vane angle or air velocity was increased.

2. LBO improved when outer swirl intensity was increased. When inner air velocity was higher than outer air velocity, co-swirl yielded slightly lower values of LBO than the counter-swirl arrangement. However, LBO values remained unchanged for equal inner and outer velocities.

3. An optimum hardware and flow configuration for the SSC was found for inner vane angle = 45°, outer vane angle = 60°, co-swirl direction, and inner air velocity = outer air velocity = 16 m/s. This configuration yielded: (i) low LBO values, (ii) short flame length, (iii) uniformly mixed stable flame, and (iv) little or no variation in these characteristics over the SSC range of operation.

4. Photographs indicated and LDA velocity measurements confirmed that the co-swirl flame has a dimple-shape, produces a slightly shorter flame stabilized by the inner recirculation zone, a lower value of LBO, and less variability of the combustion characteristics with changes in hardware and flow conditions. In contrast, the counter-swirl flame has a bulb-shape which fully confines the bluish, partially premixed combustion process to the center of the combustor dome, requires a slightly higher value of LBO, and needs a longer combustor dome length to confine it. These important differences between the two swirling arrangements can influence the off-design performance of the combustor.

5. Finally, no noticeable change was observed in the flame size and shape over a range of test conditions when the combustor was operated with the optimum configuration. This knowledge should be of value to the combustor designer.

ACKNOWLEDGMENTS

This work was supported by the U.S. Air Force, Wright Laboratory, Fuels and Lubrications Division, Aero-Propulsion and Power Directorate, Wright-Patterson Air Force Base, Dayton, OH under contract No. F33615-92-C-2207, with Mr. Charles W. Frayne serving as the Air Force Technical Monitor. The authors wish to thank Drs. G. J. Sturgess and W. M. Roquemore for valuable discussions, and Mr. M. D. Vangsness for his help with the LDA measurements.

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