FLAME AND FLOW TOPOLOGIES IN AN ANNULAR SWIRLING FLOW

I. Chterev\textsuperscript{a}, C.W. Foley\textsuperscript{a}, S. Kostka\textsuperscript{b}, A.W. Caswell\textsuperscript{b}, N. Jiang\textsuperscript{b}, J.M. Seitzman\textsuperscript{a}, T.C. Lieuwen\textsuperscript{a}

\textsuperscript{a}School of Aerospace and Mechanical Engineering, Georgia Institute of Technology, Atlanta GA
\textsuperscript{b}Spectral Energies, LLC, 5100 Springfield Street, Ste. 301, Dayton, OH 45431

ABSTRACT
A variety of different flame configurations and heat release distributions, with their associated flow fields, can exist in high swirl, annular flows. Each of these different configurations, in turn, has different thermoacoustic sensitivities and influences on combustor emissions, nozzle life, and liner heating. These different configurations arise because at least three flame stabilization locations are present, associated with the inner and outer shear layers of the annulus, and the stagnation point of the vortex breakdown region.

This paper discusses the flame and flow topologies that exist in these flows. These results illustrate the importance of the sensitivity of flame configurations to geometric (such as centerbody size and shape, combustor diameter, exhaust contraction) and operational (e.g., bulkhead temperature, preheat temperature, fuel air ratio) parameters. We particularly emphasize the centerbody shape as differentiating between two different families of flame shapes. Results are shown illustrating the time averaged and instantaneous flame shape and flow fields, using high speed PIV, OH-PLIF, and luminosity imaging.

NOMENCLATURE

CIFS Combustion induced flow separation
\(D_{CB}\) Centerbody diameter
\(\text{ISL}\) Inner shear layer
\(\text{IRZ}\) Inner recirculation zone
\(K_a\) Karlovitz number, \(K_a={\kappa}/{\kappa_{\text{ext}}}\)
\(\text{OSL}\) Outer shear layer
\(\text{ORZ}\) Outer recirculation zone
\(p_{\text{RMS}}\) RMS acoustic pressure
\(S_m\) Momentum base swirl number
\(T_{ad}\) Adiabatic flame temperature
\(T_{bdh}\) Bulkhead corner temperature
\(T_{CB}\) Center body corner temperature
\(T_{ph}\) Preheat temperature of reactants
\(U_{pm}\) Premixer (swirler inlet) velocity
\(\text{VBB}\) Vortex breakdown bubble
\(\varepsilon_{\text{annulus}}\) Post-swirler annulus contraction area
\(\varepsilon_{\text{exhaust}}\) Exhaust nozzle contraction area
\(\phi\) Fuel/air equivalence ratio
\(\kappa\) Flame stretch rate
\(\kappa_{\text{ext}}\) Extinction stretch rate

INTRODUCTION
The objective of this paper is to consider the factors influencing heat release distribution, or more fundamentally, flame position and stabilization locations, in premixed combustors. In particular, we focus on swirling flows with a center body, a common geometry for both commercial low NO\textsubscript{x} combustor hardware \cite{1, 2} and in fundamental studies of swirling flows \cite{3, 4}. This paper continues work from our group described in Refs. \cite{18} and \cite{36}, by exploring a broader geometric space and the dynamics of the flow and flame. This study provides understanding of the flowfield and flame stabilization locations’ sensitivity to geometry.

Figure 11 in the results section illustrates the key fluid dynamic features in an annular, swirl flow, along with a typical average flow field \cite{18} for a flame stabilized in the inner shear layer (ISL). The flow field of this geometry, in a time-averaged sense, consists of four main regions \cite{5, 6, 7}, as shown in Figure 11: (1) the outer recirculation zone (ORZ), a toroidal recirculating region generated by the rapid expansion of the nozzle into the combustor, (2) the center body wake and inner recirculation zone (IRZ), also referred to here as the vortex breakdown bubble (VBB), due to vortex breakdown accompanying the swirling flow, (3) the high velocity, annular fluid jet which divides these regions, and (4) two annular shear layers which divide the ORZ and annular jet, and IRZ and annular jet, denoted here as the OSL and ISL, respectively. Depending on the swirl number, size of the center body and...
Reynolds number, the center body wake and VBB can exist as a single, merged IRZ structure, or two distinct structures [15].

A key focus of this study is the types of flame shapes which can occur, the conditions under which the flame shape changes, and the unsteady features of the flow. Figure 1 illustrates typical flame configurations which exist for this geometry. Note that there are three basic flame holding locations: (1) OSL (see configurations b and d), (2) ISL (configurations c and d), and (3) stagnation point of the vortex breakdown bubble, VBB (configurations a and b). Note that a lower stagnation point may not exist inside the flow for the IRZ if the center body wake and VBB are merged. While this study focuses on a single nozzle in a circular combustor, the same basic flame stabilization locations also occur with multi-nozzle or annular combustor arrangements.

![Flame configurations](image)

**Figure 1: Illustration of flame configurations possible for geometry of interest**

The location and spatial distribution of the flame in a combustion chamber are fundamental problems which have important ramifications on combustor operability, durability, and emissions. Flame stabilization location controls the flame shape which, in turn influences heat loadings to combustor hardware (e.g., center body, combustor liner, dome plate). For example, the heat transfer to the center body is different in configurations (c) and (d) than in (a) and (b). This, in turn, has implications on center body design and life. Similarly, the flame length varies between, for example, configurations (b) and (c), causing significant differences in liner heat transfer distributions.

Next, flame location has important influence on combustion instability boundaries [8]. As is well established, combustor stability limits are controlled by the time delay between when a fuel/air ratio disturbance or vortex is created and when it reaches the flame. This time delay is a function of parameters such as flame standoff location and flame length and, as for example, varies between configurations (a) and (d). This also illustrates that discontinuous changes in combustor thermacoustic stability behavior may occur when the flame abruptly bifurcates from one stabilization location to another.

Additionally, stabilization locations (or lack of potential stabilization locations, such as if no forward stagnation point is present) influence the blowoff limits of the system. In reality, shifts in flame location can be thought of as a sequence of local blowoff events; e.g., flame configuration (d) bifurcates to configuration (b) due to local blowoff of the flame from the center body shear layer.

Flames can hold in either low velocity regimes in the shear layer, or near stagnation points associated with the vortex breakdown bubble. Because of the center body, there is a low velocity region in the separating shear layer where the flame can stabilize. However, shear introduces aerodynamic stretching on the flame [9], which alters the local temperature and burning rate [10]. If the shear strain rate and consequent flame stretch rate are too large, the flame will locally extinguish and either blow out of the combustor completely, or stabilize at another location, such as transitioning from configuration (d) to (c) or from configuration (c) to (a).

Key physical processes influencing shear layer flame stabilization include flame stretch, heat loss, heat gain, and product recirculation. Stretch induced extinction processes can be scaled with the Karlovitz number, Ka, given by:

$$Ka = \frac{\kappa}{\kappa_{ext}}$$

where $\kappa$ and $\kappa_{ext}$ denote the flame stretch rate and extinction stretch rate, respectively. Stretch induced extinction leads to strong sensitivities of shear layer stabilized flames to fuel composition, fuel/air ratio, preheat temperature, and other parameters influencing kinetic rates. For example, doping CH$_4$ flames with H$_2$ broadens the range of fuel/air ratios over which they can be stabilized, because of the increase in extinction stretch rate (ref 38).

Product recirculation also influences the mixtures kinetic characteristics when they mix with reactants in the shear layer if the reaction zone is lifted. This leads to dilution, but also preheating and radical introduction to the reactants in the separating shear layer. Both the flame speed and extinction stretch rate increase substantially with hot products dilution [25]. Furthermore, at high dilution/preheating levels, the flame speed, temperature, etc. do not have "S-curve" characteristics [10] and, consequently, the flame does not have a sharp extinction boundary. Similarly, calculations and measurements in stretched flames show that flames do not extinguish above a certain reactant temperature [25].

Heat loss and gain processes also influence flame stabilization limits. These include heat loss to the combustor walls from recirculating gases, heat loss to the bulkhead from recirculating gases, heat losses from the flame leading edge to the bulkhead, heat losses from the flame to recirculating gases, and reactant boundary layer preheating. Heat losses to the recirculating gases has been emphasized in recent studies [14], who have noted that the fact that the recirculating gas temperature is below the adiabatic flame temperature, because of heat loss, leads to heat loss from the flame to the products. Heat losses to the bulkhead wall from the flame leading edge can directly lead to flame extinction, as shown in several studies [29, 30, 31, 32]. However, these same heat losses can be recovered by preheating of the boundary layer of the
approaching flow, which has a positive influence on flame stabilization.

The rest of this paper describes studies to further characterize the different flame shapes which can exist in this geometry, and its sensitivities to underlying parameters.

**Experimental Setup**

**Combustor Design**

The experimental facility is was discussed in Ref. [36] and can be divided into a reactant supply system, flow preconditioning and fuel/air mixing, premixer, combustor, and exhaust sections. Upon entering the premixer section the outer and inner diameter of the test section are smoothly transitioned to the desired dimensions of 62 mm for the outer diameter and 36 mm for the inner or centerbody diameter.

The flow then passes through the aerodynamic swirler, which has a vane trailing edge angle of 45 or 37 degrees. Using expressions from Beer and Chigier [24], approximate swirl numbers $S_m$ are calculated as 0.8 and 0.6 for the 45 and 37 degree blade angles for a centerbody diameter of 36 mm, respectively. The momentum based swirl number for the 45 degree swirler and 36 mm centerbody has been calculated numerically as $S_m = 0.73$ at the dump plane [18]. When a larger centerbody is used, the corresponding swirlers produce higher swirl numbers with the same vane angles of 37 and 45 degrees.

We measured static pressures about 50 mm before and after the swirler vanes for the small and large centerbodies for a vane angle of 45 degrees. We obtained 0.4% and 0.6% static pressure drop for the smaller and larger centerbody, respectively.

Two different centerbody geometries are discussed in this paper, referred to as “bluff” and “spiked”. For the bluff centerbody, the inner and outer diameters of the swirler annulus remain unaltered until the dump plane. The spiked centerbody tapers down to a point at the dump plane. The spiked centerbody geometry is also accompanied by a contracting sleeve, defining the outer annulus diameter, which allows control over the flow acceleration over the spiked centerbody. The taper on the sleeve begins at the same axial location as the taper in the spiked centerbody.

The flow then enters the combustor section which consists of a 135 mm diameter quartz tube section which is 202 mm or 1.5 D long. A photograph of the annular nozzle exit and quartz tube combustor is shown in Figure 2. The exit of the combustor is a smoothly converging nozzle that provides selectable contraction ratios of 1.5 or 4.5 for reacting conditions, and additionally 9.2 and 17 for non-reacting. Figure 3 compares the bluff and spiked geometries side by side with relevant nominal dimensions.

In addition to the nominal geometry described above, for the bluff centerbody, a larger centerbody with corresponding 37 and 45 degree swirlers, and a smaller can diameter (also 1.5 D long) can be independently installed. The exhaust contraction ratio for the smaller diameter can was fixed at 1.8. The spiked centerbody had a single diameter but two can diameters.

The bulkhead is manufactured from stainless steel, the centerbody from brass, and they are instrumented with thermocouples. The bulkhead thermocouples are spaced evenly in the azimuthal direction, 2 mm radially outward from the annulus outer diameter, and 2 mm below the surface (upstream), as shown in Figure 2 (point C). Similarly, the centerbody thermocouples are evenly distributed azimuthally, 2 mm radially inward from the annulus inner diameter, and 2 mm below the surface (upstream), as shown in Figure 2 (point B). The bulkhead and center body temperatures reported in this paper are the azimuthal average of the three thermocouples at radial locations C and B, respectively. The other temperature measurements located at points A, D, E and F in the figure are not reported in this paper.

![Figure 2: PIV/OH-PLIF side view interrogation region (left) and thermocouple installation diagram (right); radial-tangential interrogation region not shown](image)

![Figure 3: Schematic of test section with nominal bluff and spiked centerbody geometries (Not to scale. Linear dimensions in mm.)](image)
collection. Data is acquired at 5 kHz, 2000 frames at a time, with a pulse separation varying from 5 to 30 μs. The camera resolution is 1024 by 592 pixels. The flow was seeded with 1-2 μm alumina particles. The seeding system consisted of a passive agitation, swirling seeder, that operated with about 5% of total air flow. The seeding particles were injected 10 cm upstream of the combustor, to ensure uniform seeding density.

This seed particle size was chosen in order to optimize between competing issues of test run time and the ability of the particles to follow the flow. The 1-2 micron seeding particle size was the smallest that could be used without window fouling becoming a major problem. The 1-2 micron gave about 0.5 s of seeding before the windows were clouded. In turbulent, swirling flows of this nature, it is important to consider what dynamic range of fluctuations the particles respond to, as well as how strong the mean radial velocities are that are induced by the centrifugal force due to the azimuthal flow velocity. We can bound the radial drift velocity by the maximum velocity seeding particles can achieve for a given centripetal acceleration. Assuming Stokes flow relations, the terminal radial velocity of a spherical seed particle scales quadratically with the diameter, inversely with absolute viscosity, and linearly with acceleration (centripetal acceleration). As such, the centrifuging effect is most important near the nozzle outlet where the temperature is low (and, therefore, the viscosity) and the azimuthal velocity high. For example, with 5 μm particles this effect is strong enough to render the almost complete absence of seeding particles in the annular jet, and hence, the inner recirculation zone. In contrast, no visible particle separation due to centrifuging was observed at the combustor dump plane for the 1-2 μm particle size. Assuming 366 K gas temperature, 1-2 μm particles and using measured azimuthal velocities of about 20 m/s, the radial velocity bias was calculated to be about 0.25-1 m/s at the dump plane. It decays to 0.06-0.25 m/s two CB diameters downstream in the reactants, as the azimuthal velocity decays to about 10 m/s. These numbers are a factor of 3 smaller in the products due to higher viscosity.

Consider next the frequency response of the 1-2 μm particles. According to formulas 24b and 25 from reference 39, the cutoff frequency scales linearly with kinematic viscosity, and inversely with the square of the particle diameter. The 1-2 micron particle cutoff frequency, based on 50% energy following, was calculated to be 4-16 kHz for 366 K preheat, using the same formulas. These values increase by a factor of more than 10 in the products due to the much higher kinematic viscosity.

A combination of spherical and cylindrical lenses is used to prepare a laser sheet of a nearly uniform thickness of 2 mm. The relatively high sheet thickness used here is necessary to reduce loss-of-pairs error, a significant issue in swirl flows due to out of plane motion. The laser sheet is aligned to within 0.5 mm to the combustor centerline, and enters vertically through the top of the combustor, as shown in Figure 2. In order to have sufficient camera pixel illumination by the seeding particles as required by the DaVis software by LaVision, the camera viewing window size could only encompass at most one third of the combustor. As a result three separate viewing windows were required to capture the entire combustor. The velocity fields were calculated using the Da Vis 7.2 software from La Vision. Noise introduced by background illumination and reflections from the quartz tube was reduced using by subtracting a sliding minimum over time image from the raw images. Then, a multi-pass calculation with a final interrogation window size of 32 by 32 pixels is used to calculate the instantaneous velocity fields. Median filtering and physical bounds for the allowed velocities were applied to each instantaneous field to remove spurious data.

The high swirling component throughout the combustor combined with significant range in axial velocity, and regions of high shear, required special attention in PIV data collection. The swirling component has been verified with LDV measurements to persist with little decay along the entire combustor. Away from the combustor centerline the azimuthal velocity component is high, peaking at ~35 m/s, and does not decay significantly with distance downstream. The azimuthal velocity component is generally on the same order of magnitude as the axial component, and is significantly larger than it in some locations, such as the shear layers and stagnation planes in the recirculation zones. This requires the shape of the interrogation volume, defined by the interrogation window size in the PIV algorithm and laser sheet thickness, to be closer to a cube than the traditional nearly 2-D interrogation volume. This implies loss of resolution in the depth of the plane of measurement. Ordinarily the issue of high velocity range could be overcome by using high velocity dynamic range PIV. One way is using multiple pulse separation imaging. However, the long time separation measurements needed to capture the low axial/radial velocity regions is limited in accuracy by loss-of-pairs error introduced by swirl-induced out of plane motion. Features such as the inner recirculation zones can be enhanced a little by using longer time separation, but any location significantly away from the centerline requires lower time separation to reduce loss-of-pairs due to out-of-plane motion.

In addition to quantitative velocimetry measurements, the raw Mie scattering images obtained during PIV measurements are also useful for flow visualization, such as shown in Figure 4 for the bluff centerbody.
Figure 4: Instantaneous Mie scattering images (sliding background subtracted) from bluff centerbody, nominal geometry, $U_{pm}=35$ m/s, $T_{ph}=366$ K

**High Speed OH-PLIF System Setup**

High speed PLIF measurements was performed using an Nd:YAG pumped dye laser. The pump laser, a 10 kHz DPSS Nd:YAG laser with an output of about 4 mJ/pulse, acts as a pump to a tunable wavelength Sirah Credo dye laser. The dye laser consists of modified dye pumps, oscillator and amplifier cells capable of handling the high power, and a high repetition rate pump source enabling maximum UV output of about 200 $\mu$J/pulse. The UV output was tuned to a transition wavelength of OH around 283nm. The fluorescence signal is collected with a high speed LaVision IRO image intensifier coupled to a high speed Photron SA1 CMOS camera. The intensifier allows for the collection of the UV light while also providing gating control to minimize interferences from flame emission.

**Results**

This section describes the different flame and flow topologies that are possible with annular swirl geometries. As noted in Figure 11, there are three potential flame stabilization locations. The basic features and controlling parameters for the shear layer stabilized flames are reasonably well understood, but the factors under which aerodynamic stabilization occurs are much less so. It is clear that the interaction between the centerbody wake and VBB is key to the characteristics of these aerodynamically stabilized flames, and whether they can exist at all. As such, we divide the rest of this section into two main sections, based on the bluff and spike centerbody, whose key differences appear to be in the interaction between the centerbody wake and vortex breakdown region.

**Bluff Centerbody Geometry**

**Non-Reacting**

The flow field in the combustor is a strong function of the heat release rate and, therefore, it is useful to start with nonreacting results. The time averaged non-reacting flowfield is illustrated in Figure 5. Note the presence of reverse flow all the way to the bluff body - i.e., separate VBB and centerbody wake features are not observed. The VBB persists all the way through the exhaust so that there is reverse flow at the exhaust. The inner and outer recirculation zones are toroidal.

Figure 5: Flowfield for non-reacting conditions (nominal geometry, $U_{pm}=35$ m/s, no preheat)

The presence of the aft stagnation point inside or outside of the combustor is a function of the exhaust contraction ratio and, in the reacting cases, the fuel/air ratio as well. To illustrate, Figure 6 shows the effect of exhaust diameter on the axial centerline velocity profile for $U_{pm}$ of 35 m/s. It can be seen that for the contraction ratios tested which were larger than the nominal 1.5, the VBB closes out inside the combustor.

Figure 6: Effect of contraction ratio on centerline velocity in non-reacting flow for otherwise nominal geometry at $U_{pm}=35$ m/s
Observed Flame Shapes

Four different flame configurations are observed for this combustor geometry. Figure 7 shows Abel inversions of the time averaged luminescence images of the different flame configurations, illustrating the bifurcations in flame shape that occur as the equivalence ratio is steadily increased. Similar flame shapes and transitions have also been noted in other studies on annular, swirling geometries [20, 21]. With this geometry, the flame configuration shown in Figure 1(b) was never observed. The observed flame shapes are discussed further next.

Figure 7: Time averaged Abel inverted luminosity images showing the main four different flame configurations for bluff centerbody geometry (nominal geometry, $T_{ph}=366$ K, $U_{pm}=35$ m/s)

Flame Shape I

Configuration I appears to be stabilized by the vortex breakdown stagnation point. The flame passes through the exhaust nozzle and persists a significant distance outside of the combustor. As the combustion efficiency of this configuration is quite low, we have not pursued detailed flow measurements to clarify the character of the flow field, such as near the stabilization point. LDV scans for $e_{exhaust}=1.5$ at the combustor exhaust plane confirm that there is reverse flow all the way through the exhaust.

Flame Shape II

Configurations II and III are both ISL stabilized. While stabilized at the same point, the resultant flame shape is quite different, as can be seen in the figures. Moreover, the transition between configurations II and III is abrupt. Flow field measurements show that these differences are due to the IRZ region persisting all the way through the combustor and into the exhaust in configuration II, and closing out and forming a stagnation point in configuration III [18].

This flame configuration is quite sensitive to exhaust contraction ratio which, as discussed above also has an important influence on the closeout of the IRZ. A typical measurement for a case with the nominal $e_{exhaust}=1.5$, in which the IRZ persists all through the exhaust, is illustrated in Figure 8. The heat release in this configuration is sufficient to affect the flow field significantly relative to the non-reacting case. The inner recirculation zone increases in size due to the expanding reacting gases, and increases the annular jet spread angle relative to the non-reacting case.

Figure 8: Flowfield for flame II (nominal geometry, $U_{pm}=35$ m/s, $T_{ph}=366$ K)

For higher exhaust contraction ratios, configuration II does not exist, but there is a similar flame shape stabilized simultaneously in the CB wake and ISL, which we refer to as II’. In this II’ configuration, the wake stabilized flame was weak and unsteady, see Figure 9. In addition, with the small CB and 37 degree swirler, the rig ignites in flame III, skipping both configurations I and II. Apparently, lower swirl reduces the propensity of the flame to stabilize in the VBB/CB wake, because of reduced recirculation strength. Increasing the CB diameter broadens the conditions under which I and II’ exist. Figure 10 shows the occurrence of flames I, II, and II’ in CB diameter and swirl number space for the high exhaust contraction ratio of 4.5.

Figure 9: Notional representation of centerbody wake and VBB stabilized flame II’ based upon line of sight imaging (nominal geometry with $e_{exhaust}=4.5$, $T_{ph}=366$ K, $U_{pm}=35$ m/s)
These observations also provide insight into the observations of fuel composition effects on the blowoff process of CH$_4$/H$_2$ fuel blends reported by Zhang et al. [38]. This study also used a bluff centerbody and found that, with decreasing fuel/air ratio, high H$_2$ flames transitioned from IV→III-blowoff. The low H$_2$ flame transitioned from IV→III→I→blowoff. The key difference between these two probably lies in the much lower fuel/air ratio, and therefore flame temperature ratio at blowoff for the high H$_2$ flame.

**Flame Shape III**

As the equivalence ratio is further increased for the $\varepsilon_{\text{exhaust}}=1.5$ case, the vortex breakdown structure abruptly changes and closes out inside the combustor, leading to an abrupt bifurcation in flame shape. Figure 11 shows the flowfield for flame III. In addition to the closeout of the VBB inside the combustor, the centerline flow has positive, rather than reverse flow, velocity. This is fundamentally different than the recirculating flow field with negative centerline velocity throughout the combustor for isothermal non-reacting and flames I and II cases. All of the OH PLIF images shown later show a dark region in the centerbody region, indicating either "cold products" or reactants in this space. Further measurements are needed to determine whether this positive axial jet and this "dark region" are related.

The two largest contraction ratio cases studied for non-reacting conditions were characterized by a centerline velocity which was negative in the centerbody wake and, after a stagnation point, became positive and remained such throughout combustor. This behavior suggests distinct centerbody wake and inner recirculation zone regions, as opposed to the structure observed in flame III (and flame IV), in which the centerbody wake and IRZ are merged as suggested by PIV data. Figure 12 shows the centerline velocities from PIV data for non-reacting, flame III, and flame IV (nominal geometry, $U_{pm}=35$ m/s, $T_{ph}=366$ K). As this flame shape is of significant practical interest, we also discuss its instantaneous features. Figure 13 illustrates typical instantaneous OH-PLIF images of this configuration. The figure illustrates the presence of small scale fluctuations of the flame sheet, presumably associated with rollup of the shear layers. Interestingly, no large scale undulations or corrugations of the flame are present in any of the images. Similar conclusions can be reached from the Mie scattering image in Figure 4 or vorticity plots.

III’s centerline velocity is very close to zero near $x/D=0.75$, but that is due to the flow centerline being displaced relative to the geometric centerline.

---

**Figure 10:** Possible flame shapes observed for higher contraction ratio cases ($\varepsilon_{\text{exhaust}}=4.5$) and otherwise nominal geometry where VBB closes out inside combustor for non-reacting cases

**Figure 11:** Flowfield for flame III (nominal geometry, $U_{pm}=35$ m/s, $T_{ph}=366$ K), 1) ORZ, 2) IRZ, 3) Annular Jet, 4) Shear Layers, 5) Central Jet

**Figure 12:** Centerline velocity from PIV for non-reacting, flame III, and flame IV (nominal geometry, $U_{pm}=35$ m/s, $T_{ph}=366$ K)
Some images also suggest that the flame instantaneously lifts off of the shear layer, with a leading edge that bounces back and forth axially, such as the top flame branch in the right image. OH-PLIF images taken along the $r$-$\theta$ cut near the dump plane (Figure 14) suggest that a portion of the flame lifts off, and that this region spins around the centerbody edge. For example, note the dark central regions of the two instantaneous images in Figure 14, demonstrating the absence of OH radicals. This feature is consistent with the idea that a portion of the flame has lifted off from the dump plane. One can also note this behavior upon close inspection of the OH-PLIF images in Figure 13. Note the difference in the axial location of the attachment point in the top and bottom views of the ISL. The rotation of the dark region noted in the $r$-$\theta$ OH-PLIF images, is apparent in the $r$-$z$ plane as the flame detaches from either the bottom or top view of the ISL but never for both in the same instant.

OH PLIF images taken along $r$-$\theta$ cuts farther downstream are shown in Figure 15. Here, no rotating flame hole regions are present and the radial expansion of the flame is clear. In addition, note that while small scale flame wrinkling is present, no large scale corrugations of the flame are present. This observation is similar to Figure 13.

**Flame Shape IV**

Further increases in equivalence ratio cause the flame to abruptly anchor in the outer shear layer as well. The fact that the flame can stabilize in the ISL over a broader range of conditions is likely a manifestation of the fact that the ISL shear layer is thicker, due to the adverse pressure gradient imposed by the recirculating flow. This causes the flame stretch rates to be higher for OSL stabilization. In addition, the OSL flame has higher heat losses associated with the outer recirculating flow because of the combustor walls. This observation is supported by RANS studies with adiabatic combustor walls, which show that as the equivalence ratio increases, the flame attaches almost simultaneously to the inner and outer shear layers [34, 35].

Two features of interest are noted in this flow field relative to flame III. The outer recirculation zone bifurcates into a two stage annular structure. This is likely due to the accelerated hot gases produced at the OSL flame; this also leads to the presence of a vortex near the combustor corner rotating counter to the direction of rotation without heat release. The second feature of note is the decreased jet spread angle as a result of the hot products escaping from the OSL stabilized flame.
As discussed previously [36], the transition points between these different configurations were characterized as a function of fuel/air ratio, preheat temperature, bulkhead temperature, and center body temperature. Figure 17 shows a typical flame configuration run, showing the OSL stabilization and blowoff lines. In some cases, there is also significant hysteresis between the equivalence ratios associated with these transitions. The hysteresis zone in equivalence ratio, and bulkhead temperature space is shown in Figure 17. The mechanisms responsible for hysteresis are still under investigation, but they are clearly related to the presence of acoustic oscillations and the ratio of $T_{ad}$ to $T_{ph}$, as well as other processes still to be determined.

As discussed in the previous paper [36] we can successfully model the sensitivity of attachment in the OSL to premixer velocity using our $\kappa_{ext}$ scaling.

Some instantaneous OH-PLIF images for flame shape IV are shown below. As was noted for flame shape III, there is no large scale wrinkling of the inner or outer flame branches. Small scale structures are present in both shear layers and visible in the $r-z$ (Figure 18) and $r-\theta$ (Figure 19) planes. The nature of the flame wrinkling changes downstream as well. In Figure 20, one can see how at certain times, the wrinkle scales are larger than those present closer to the dump plane and flame attachment point (Figure 19).

As was similarly noted for flame shape III, there is a dark central region in the OH-PLIF images of flame shape IV in the $r-\theta$ plane just downstream of the dump plane. This local region of flame detachment rotates around the combustor axis and is visible in the $r-z$ plane as it causes either the top or bottom ISL stabilized flame to detach from the dump plane.
Spiked Centerbody Geometry

Observed Flame Shapes

In this section we consider the key changes associated with modification of the centerbody characteristics. The spiked geometry leads to an additional flame shape. The absence of a bluff centerbody eliminates the associated large wake and no ISL stabilized flame is observed, except in cases where the flame partially flashes back. As we ignite from the lean blowout limit and gradually increase the equivalence ratio, we generally observe four flame shapes which are shown in Figure 21. The leanest flame, configuration I, is again a VBB stabilized flame which is very weak and extends outside of the combustor. Further increases in equivalence ratio cause this flame to abruptly change shape as the VBB closes out inside the combustor, referred to as Configuration I’. Such an aerodynamically stabilized flame that consumes the majority of the reactants inside the combustor was never observed for the bluff centerbody.

Further increases in equivalence ratio produce an M-shaped flame, IV’, which is VBB/OSL stabilized. This flame configuration was previously noted by Bellows and Lieuwen [37] in a configuration with a smaller, but still somewhat bluff centerbody.

Further increases in equivalence ratio can lead to combustion induced flow separation (CIFS) along the centerbody, leading to flame stabilization upstream of the combustor inlet. In this combustion induced separated case, the flame shape looks like the original flame IV.

Deviations from the above sequence I→I’→IV’→IV are sometimes observed and will be discussed under flame I’. Furthermore, if the geometry is conducive to flow separation for the non-reacting case, then the bluff centerbody flame shape sequence is observed I→II→IV. The absence of flame shape II can be attributed to the smaller centerbody wake.

Flame Shape I’

Flame I’ provides significant heat release while also being detached from all combustor surfaces. No such configuration with both these properties was observed with the bluff centerbody. The flow field associated with flame I’ is shown in Figure 22. The aft stagnation point is located inside the combustor, but no central jet exists in the IRZ.

With the smaller can flame I’ was not observed and the combustor transitioned directly from I to IV’. Since the exhaust contraction ratio is maintained roughly the same for the two different combustor diameters we can rule out a contraction ratio effect. This effect is possibly caused by a combination of the increased heat loss from the outer region and confinement on the IRZ structure. We note in passing that no CIFS on the centerbody was observed for this smaller can diameter case either.

Flame Shape IV’

The flow field associated with flame IV’ is shown in Figure 24. Note the shortening of the IRZ zone and the decrease in the
jet spread angle due to the gas expansion in the ORZ, much like the difference between flames II and IV before.

Configuration IV' persisted with increasing equivalence ratio until abruptly bifurcating into a flame resembling IV, where the flame is stabilized by the separating boundary layer inside the nozzle. As expected, CIFS occurs in a broader range of conditions at high swirl numbers. CIFS is inhibited by increasing the area contraction ratio in the nozzle section, which decreases the adverse pressure gradient along the centerline because of the bulk flow acceleration. Figure 23 illustrates the effects of swirl number and post-swirler contraction ratio on the presence of flame IV' at high equivalence ratios.

![Figure 23: Notional representation of swirl number and post-swirler annulus contraction effects on flame IV' presence at high equivalence ratios for spiked centerbody geometry](image)

Figure 23: Notional representation of swirl number and post-swirler annulus contraction effects on flame IV' presence at high equivalence ratios for spiked centerbody geometry

![Figure 24: Flowfield for flame IV' (U_{pm}=35 m/s, T_{ph}=366 K, S_m=0.6, no post-swirler annular contraction)](image)

Figure 24: Flowfield for flame IV' (U_{pm}=35 m/s, T_{ph}=366 K, S_m=0.6, no post-swirler annular contraction)

No OH-PLIF images were obtained from this configuration, but some insight into the unsteady character of the flow can be obtained from Figure 25, using the instantaneous Mie scattering images obtained from the raw PIV images. These images clearly show much larger scale structures in the flow, particularly a helical disturbance which appears to originate from the centerbody. Note also the snake-like structure visible in the inner recirculation zone, changing in length and shape with time.

![Figure 25: Mie scattering images showing helical vortex shedding from spiked CB, flame IV' (U_{pm}=35 m/s, T_{ph}=366 K, S_m=0.6, no post-swirler annular contraction)](image)

Figure 25: Mie scattering images showing helical vortex shedding from spiked CB, flame IV' (U_{pm}=35 m/s, T_{ph}=366 K, S_m=0.6, no post-swirler annular contraction)

**Concluding Remarks**

When a swirling annular combustor geometry is used many different flame shapes and associated flowfields can exist, depending on the choice of swirl number, centerbody and combustor diameter, and exhaust contraction ratio. Replacing a bluff centerbody with a spiked one results in another set of flame shapes. Some flame shapes are of little interest due to poor efficiency or low power such as some of the vortex breakdown bubble stabilized flames. Others are of great interest due to their predictability/stability, high power and low heat transfer to combustor walls characteristics, such as the strong vortex breakdown stabilized flame observed for the spiked centerbody geometry.

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge the financial support of United Technologies Corporation for this research. They also gratefully acknowledge the assistance of Sukesh Roy and James Gord from Spectral Energies in obtaining the OH-PLIF images shown here (work supported under AFRL contract #FA8650-12-M-2218, Amy Lynch, program manager).

The following graduate students are acknowledged in particular for their help with borrowed MATLAB code: Prabhakar Venkateswaran, Benjamin Emerson, and Karthik Periagaram.

The following undergraduate students are acknowledged for their assistance in servicing the rig, setting up for experiments, and taking data: Evan Grimm, Matt Ray, Anna Hotle, and Kavin Manickaraj.
REFERENCES


[33] Smith, G.P., D.M.G., Frenklach, M., Mioriary, N.W., Eiteneer, B., Goldenberg, M., Bowman, C.T., Hanson,
R.K., Song, S., Gardiner, W.C., Lissianski, V.V., Qin, Z., http://www.me.berkeley.edu/gri_mech/ GRI-Mech 3.0