FLAME AND FLOW DYNAMICS OF A SELF-EXCITED, STANDING WAVE CIRCUMFERENTIAL INSTABILITY IN A MODEL ANNULAR GAS TURBINE COMBUSTOR

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ABSTRACT
Azimuthal instabilities are prevalent in annular gas turbine combustors; these instabilities have been observed in industrial systems and research combustors, and have been predicted in simulations. Recent experiments in a model annular combustor have resulted in self-excited, circumferential instability modes at a variety of operating conditions. The instability mode “drifts” between standing and spinning waves, both clockwise and counter-clockwise rotating, during the course of operation. In this study, we analyze the flame response to standing wave modes by comparing the flame dynamics in a self-excited annular combustor with the flame dynamics in a single nozzle, transverse forcing rig. In the model annular combustor, differences in flame fluctuation have been observed at the node and anti-node of the standing pressure wave. Flames at the pressure anti-node display symmetric fluctuation, while flames at the pressure node execute asymmetric, flapping motions. This flame motion has been measured using both OH* chemiluminescence and planar laser induced fluorescence of OH radicals. To better understand these flame dynamics, the time-resolved velocity fields from a transverse forcing experiment are presented, and show that such a configuration can capture the symmetric and asymmetric disturbance fields at similar frequency ranges. Using high-speed PIV in multiple planes of the flow, it has been found that symmetric ring vortex shedding is driven by pressure fluctuations at the pressure anti-node whereas helical vortex disturbances drive the asymmetric flame disturbances at pressure nodes. By comparing the results of these two experiments, we are able to more fully understand flame dynamics during self-excited combustion instability in annular combustion chambers.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>D, D_{out}</td>
<td>Outer diameter of nozzle</td>
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<td>D_{in}</td>
<td>Inner diameter of nozzle</td>
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<tr>
<td>\rho</td>
<td>Pressure</td>
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<tr>
<td>q</td>
<td>Heat release rate</td>
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<td>R</td>
<td>Radius of centerbody</td>
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<td>\bar{u}</td>
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<td>\omega</td>
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INTRODUCTION
Combustion instability, a coupling between resonant combustor acoustics and heat release fluctuations from the flame [1, 2], is one of the foremost challenges in gas turbine design and operation. These instabilities have been reported across different engine platforms and operating conditions [3], and can couple with a variety of acoustic modes within these engines. The focus of this study is the coupling of the flame with circumferential acoustic modes in annular combustors. Annular combustors are used in both land-based, power generation platforms as well as aero-engines, and circumferential instabilities have been observed in both combustor architectures [3]. Specific issues pertaining to
circumferential, also known as azimuthal, instabilities in these technologies have been well reviewed in several references, see Ref. [4-6].

Early on, in an attempt to understand flame response to transverse instability modes, researchers tested similar flame configurations at azimuthal instability frequencies in longitudinally forced systems [7]. While certain important flame response characteristics can be gleaned from longitudinal experiments [8-14], there are additional flame response pathways present during transverse acoustic excitation that do not necessarily exist in the longitudinal forcing case [15]. Several studies have investigated the specific case of azimuthal instabilities, including aspects of the self-excited instability in realistic annular combustor geometries [16-20], experimental studies on model annular combustors [21, 22], and investigations of flow and flame dynamics in transverse forcing facilities [15, 23-26]. We briefly highlight some of the pertinent findings in this literature.

Investigations into the self-excited behavior of azimuthal instabilities in annular gas turbines have shown that these instabilities can take the form of either standing or spinning waves [19, 27]. In the case of the standing waves, the clockwise (CW) and counter-clockwise (CCW) rotating waves have the same amplitude and constructively interfere to form a standing wave pattern. These waves must not necessarily have the same amplitude, however, and if one wave amplitude is greater than the other, a rotating acoustic mode will occur [20]. As these systems are nominally symmetric, the occurrence of one form of the instability over another is somewhat stochastic.

Recent experiments and simulations in the model annular combustor in the current study found that the instability alternated between standing or spinning mode [21]. The likelihood of one mode over another was a function of both the swirl configuration and the flame separation distance. For an alternating swirl configuration, that is one in which adjacent flames are subject to swirl of opposite orientation, standing wave modes were found to dominate. However, when all swirlers had the same orientation, increasing the separation distance between adjacent flames changed the mode preference from CCW spinning modes to standing and then CW spinning modes. Initial measurements of flame response using chemiluminescence imaging from an overhead view indicated that flames may be responding differently at different locations in the acoustic mode. This finding is investigated further in the current study.

Detailed investigations of flame response to transverse acoustic forcing have been made using transverse acoustic forcing rigs that mimic the acoustic field in an annular combustor without the infrastructure of an annular rig [23-25]. These experiments have shown that response of a swirl-stabilized flame to transverse acoustic excitation can be different from the response to longitudinal excitation. Figure 1 describes the pathways established for flame response to transverse acoustic excitation.

In the case of longitudinal forcing, both acoustic and vortical velocity disturbances are possible during velocity-coupled combustion instability. The acoustic disturbances are a result of longitudinal, symmetric fluctuations through the nozzle, and these acoustic velocity oscillations can lead to coupling with vortical velocity fluctuations at boundaries. For example, coupling between the acoustic fluctuations and the hydrodynamically unstable features of the flow, such as the shear layers and vortex breakdown bubble, has been shown to lead to significant flame response [28-30]. Additionally, swirl flow fluctuations that stem from the interaction of the acoustic fluctuations with the swirler can also lead to flame heat release fluctuations [10, 31].

In the case of transverse instabilities, additional pathways can be excited. For example, the flame can respond directly to the transverse acoustic velocity fluctuations [32], given by $F_T$ in Figure 1. Additionally, the transverse acoustic field can couple with the nozzle acoustics, producing a longitudinal acoustic fluctuations in the region of the flame [33, 34], given by $F_{TL}$. This coupling has been long established in the rocket community, and is known as “injector coupling” [35-37]. Pressure fluctuations at the exit of the nozzle create a fluctuating pressure drop across the nozzle. This forces a longitudinal mass flow fluctuation through the nozzle and leads to more symmetric (typically longitudinal) pathways of flame response. The acoustic aspect of this coupling has recently been investigated in a gas turbine-type nozzle configuration by Blimbaum et al. [38]. Finally, both these acoustic motions can couple with flow instabilities, resulting in vortical velocity disturbances that lead to flame response, given by $F_{o}$ in Figure 1.

One of the common observations from both annular rigs and transversely forced experiments is that the flow and flame response are highly dependent on where the nozzle is located with respect to the acoustic field. When the nozzle was situated...

**Figure 1. Flame response pathways in a flame subject to transverse acoustic excitation [15].**
at the pressure node, a helical response in the flame was measured. At the pressure anti-node, however, the flame response was more axisymmetric and looked similar to that of a longitudinally forced flame [23]. This type of motion was also observed in LES simulations by Staffelbach et al. [20].

These differences stem from the response of the flow field to different forcing symmetries. As a result of the symmetry boundary condition that the acoustic field imposes on the flow field, the response of the flow field changes with variations in the acoustic field symmetry. Examples of the role of acoustic field symmetry in flow response have been measured in circular, non-reacting jets. Symmetric, longitudinal forcing of circular jets results in the shedding of ring vortices from the jet exit [39, 40]. Asymmetric forcing has been shown to result in highly asymmetric flow response, particularly in the case of bifurcating and blooming circular jets [41]. Swirling jets, like those in the current study, respond with similar characteristics. Work by O’Connor and Lieuwen [15, 23, 42] has shown that forcing symmetry has a similar effect on swirling jets, where symmetric forcing results in ring vortex shedding and asymmetric forcing results in helical vortex shedding. Likewise, recent experiments in the model annular combustor by Worth and Dawson [21] have shown that the symmetry of the flame response is also a function of the acoustic forcing symmetry.

The goal of this work is to compare and contrast these observations between an annular combustor and a transverse forcing facility. This comparison will be useful for not only furthering our understanding of flame response to azimuthal instabilities, but also help us to better translate results from these “reduced-order” rigs like the transverse forcing facility to full annular configurations. It is not the goal of this work to quantitatively compare the results from these two experiments; these facilities were designed and operated completely independently of each other. However, the flame response characteristics in these experiments are quite similar, despite the differences in geometry. The results presented here support the notions that a) transverse forcing experiments can faithfully capture flame response characteristics of azimuthal instabilities and b) there is much that can be learned by analyzing data from both types of experiments in concert. We hope that this study will provide a stepping-stone for further investigation of transverse instabilities in future annular and transverse forcing facilities.

The remainder of the paper is organized as follows. We first provide an overview of each of the experimental facilities separately before discussing key points of comparison between the two. Next, we give a description of the self-excited standing wave instability in the annular rig, including details of the acoustic mode and global flame response. This is followed by a detailed description of the flame response at the pressure node and anti-node in both experiments as well as high-speed particle image velocimetry (PIV) data from the transverse forcing experiment. Finally, we discuss implications for comparison of single-nozzle experiments to full annular combustors and the impacts this has on measurements of flame response for azimuthal instabilities in annular gas turbine combustors.

EXPERIMENTAL SETUP AND ANALYSIS

The results discussed in this paper were obtained from two different experiments: a model annular combustor at the University of Cambridge and a transverse forcing facility at the Georgia Institute of Technology. In this section, we discuss the details of the facilities and diagnostics separately before commenting on the comparison of a few key quantities between the two, including combustor geometries, flow fields, and flame shape.

Annular Combustor Facility and Diagnostics

The annular combustor facility consists of 18 equally spaced, bluff-body stabilized turbulent premixed flames placed in an annular configuration as shown in Figure 2. Ethylene is fully premixed with air before flowing into a 200 mm long cylindrical plenum chamber with an inner diameter 212 mm. A series of grids and honeycomb flow straighteners are used in conjunction with a hemispherical bluff body to improve flow conditioning into the 150 mm long inlet ducts. Each tube of inner diameter 18.9 mm is fitted with a centrally located conical bluff-body of diameter 13 mm giving a blockage ratio of 50%. Six-vane, 60° swirlers, giving a geometric swirl number of 1.22, all have a counter-clockwise orientation. The inlet ducts are arranged around a circle of diameter 170 mm. The flame separation distance is 1.56 inlet duct diameters. The flames are confined within an annular enclosure 2.2 inlet duct diameters in width. The lengths of the inner and outer confinement are 130mm and 300mm, respectively.

![Side Schematic](image)

**Figure 2. Schematic of the annular combustor configuration at Cambridge University.**

Alicat mass flow controllers control the air and ethylene mass flows. The bulk reactant exit velocity is $u_c=18 \text{ m/s}$, which
corresponds to a Reynolds number of 22,680 based on the outer nozzle diameter. The mixture is prepared with an equivalence ratio of 0.85. Three pairs of Kulite XCS-093 pressure transducers are positioned 120° apart to characterize the instability modes. At each position, a pair of microphones are mounted flush with the inside walls of the inlet tube at two locations as shown in Figure 2. The pressure signals are acquired at 30 kHz with sample lengths of 4.3 seconds. These signals are amplified and filtered before being digitized using a National Instruments 16 bit PCI 6251 card.

The annular combustor is visualized from overhead via an air cooled mirror and angled at 45°. OH* chemiluminescence images are captured using a Photron SA1.1 high-speed CMOS camera with a 1024x1024 maximum pixel resolution coupled with a LaVision IRO high-speed two-stage intensifier, fitted with a Cerco 2178 UV lens 100F/2.8 and a UV filter (270-370 nm). 2000 images are obtained at a frame rate of 500 fps in order to compute time-average flame information. For the self-excited cases, 14328 images are captured at a frame rate of 14400 fps at a reduced pixel resolution of 628 by 640.

Time-resolved OH-PLIF is used to provide a measure of the flame structure. The imaging system consists of a 15W JDSU Q201-HD laser, which pumps a high-speed Sirah Credo 2400 dye laser, achieving 60 µJ per pulse at 5 kHz. The Q1(4,5) transition was used at approximately 283nm, the position of the transition was verified by performing a frequency sweep to locate the peak. A series of optics are used to produce a thin 25 mm high sheet whose path traverses the centers of two bluff bodies, similar to the configuration in Ref. [43]. The camera and intensifier are fitted with a Cerco 2178 UV lens 100 (F/2.8) and an OH filter (300-325 nm). 8900 images are obtained at each condition. After correcting for beam profile inhomogeneity, the flame surface density (FSD) is computed following a similar approach to Balachandran et al. [44], using an interrogation window size of 5 pixels. The FSD is used qualitatively as a flame front marker.

OH-PLIF phase-averaging is performed by first locating the pressure oscillation peaks from a single sensor, and normalizing each individual pressure cycle, and then dividing these into 18 equal normalized time bins (normalized by the local time period). An additional identification procedure is required to differentiate between travelling and standing modes, and the orientation of the latter. The local pressure fluctuations (approximately 6 cycles) at the three annular locations are evaluated to determine the closest oscillation amplitudes and angular displacement of two ideal waves travelling in opposing directions around the annulus in a least-squares sense. The ratio of the wave amplitudes is then used to determine the local azimuthal instability mode by selecting appropriate thresholds. Ratios of A+/A_ < 0.5, 0.5 < A+/A_ < 2 and A+/A_ > 2 are used to demarcate CW spinning, standing and CCW spinning modes, respectively. Images are then binned according to the local oscillation mode.

Transverse Forcing Facility and Diagnostics

The transverse forcing facility in this study is built to mimic the shape and acoustic mode of annular combustors in the region of the flame. The combustion chamber is a high aspect ratio rectangular chamber with a dimension of 114 cm in the transverse direction (direction of acoustic oscillation). 35.5 cm in the direction of flow, and only 7.6 cm in the cross-stream direction. A picture of the combustion chamber is in Figure 3, and more details of the design of the chamber can be found in Ref. [15]. Three speakers are located on tubes on either end of the combustion chamber, as shown in Figure 3. A different channel drives each set of three speakers, which allows for an arbitrary phase to be programmed between the acoustic driving on either side of the combustor. When the drivers are forced in-phase (0°), a pressure anti-node is created at the center of the experiment. When the drivers are forced out-of-phase (180°), a pressure node is created at the center. As will be shown later, the response of the velocity and vorticity fields change when the forcing conditions simulate pressure anti-node and node locations.

Figure 3. Transverse forcing experiment.

A swirler nozzle is situated at the center of the chamber with an outer diameter of 31.75 mm, inner diameter of 21.84 mm, and swirl number of 0.85. The bulk flow velocity is 10 m/s, resulting in a Reynolds number based on the outer diameter of the nozzle of 20,500. Fuel and air are completely premixed in a large chamber upstream of the swirler nozzle. The fuel is natural gas and the equivalence ratio is 0.9. This chamber not only acts to allow for significant premixing and reduction of large-scale turbulent structures through the use of perforated plates in the flow path, but it also acoustically isolates the fuel and air supply from the combustion chamber. This ensures that no equivalence ratio oscillates are present in these data.

A time-average of the flow field is shown in Figure 4, where the colorbar is non-dimensionalized by the bulk flow velocity, \( u_b = 10 \) m/s. As a result of the high-aspect-ratio shape of the combustor, the flow field is not exactly axisymmetric.
This non-axisymmetry can be quantified using azimuthal modal decomposition techniques described in Ref. [45]; the full details of this analysis are not the focus of the current work, and as such, we only provide a brief overview of the results. The flow is highly axisymmetric at \( x/D = 0 \), the first measurement location in both the high-speed PIV and OH-PLIF imaging, and remains relatively axisymmetric at \( x/D = 1 \), with slight asymmetries appearing at radii greater than \( r/D = 0.75 \). At \( x/D = 2 \), the flow is significantly asymmetric at all but the inner most radii, a result of the asymmetric boundary conditions imposed by the rectangular combustor geometry. Over this distance, however, neither the central annular jet nor the flame impinges on any surface of the combustor; these asymmetries do not result from direct contact with solid surfaces.

![Figure 4. Time-average axial velocity (color) and streamlines for the reacting flow field in the transverse forcing rig at \( u_r = 10 \) m/s, \( \phi = 0.85 \), and \( \theta = 0.9 \).](image)

A high-speed LaVision Flowmaster PIV system is operated at 10 kHz to capture the two-dimensional velocity field seeded with aluminum oxide particles with a mean diameter of 2 microns. The PIV measurements are taken in the \( r-x \) plane where \( x \) is the streamwise direction of the swirling jet and \( r \) is the radial direction. In the PIV measurements, the laser sheet enters the experiment from a window at the exit plane of the combustor and reaches a width of approximately 12 cm at the dump plane, i.e. at \( x/D = 0 \). This is referred to as the “periscope” laser configuration.

Velocity field calculations are performed using DaVis 7.2 software from LaVision. The velocity calculation uses a three-pass operation: the first pass at an interrogation window size of 64x64 pixels, and the second two passes at an interrogation window size of 32x32, each with an overlap of 50%. The spatial resolution of the velocity field is 4.5 mm/interrogation window. Each successive calculation uses the previously calculated velocity field to better refine the velocity vector calculation; standard image shifting and deformation techniques are employed in the calculation to account for regions with high shear. The correlation peak is found with two, three-point Gaussian fits, whose typical values ranged from 0.4 to 1 throughout the velocity field. There are three vector rejection criteria used both in the multi-pass processing steps and the final post-processing step. First, velocity vectors with magnitudes greater than 25 m/s are rejected as unphysical for this specific flow. Second, median filtering is used to filter points where surrounding velocity vectors have an RMS value greater than three times the local point. This filter rids the field of spurious vectors that occur due to issues with imaging, particularly near boundaries. Third, groups of spurious vectors are removed; this operation removes errors caused by local issues with the original image, including window fouling, and are aggravated by using overlapping interrogation windows. Finally, vector interpolation fills the small spaces of rejected vectors. Overall, an average of 8% of vectors are rejected and replaced with interpolated values.

The use of high-speed PIV diagnostics allows for spectral analysis of the data, which is used extensively in this study. Spectra of several quantities are calculated using fast Fourier transforms. 500 images are taken at 10 kHz, resulting in a spectral resolution of 20 Hz with a maximum resolvable frequency of 5 kHz. In this way, the amplitude and phase of fluctuations over this range of frequencies can be seen across the field of view.

Also, high-speed planar laser induced fluorescence of OH (OH-PLIF) is used to investigate flame motion in a plane. For this part of the study, a Sirah Credo amplified dye laser with rhodamine 6G dye is pumped with an Edgewave Innoslab Nd:YAG laser at 10 kHz and tuned to 283.9 nm with a pulse energy of 0.2 mJ/pulse, targeting the Q1(9) and Q2(8) transitions. The beam is expanded to a sheet that is approximately 5 cm tall at the flame. PLIF images from this experiment were processed at Cambridge in the same manner described in the previous section.

The PLIF images were taken in a plane that is 30 degrees off-axis to the PIV measurements for reasons of optical access. In the PLIF configuration, the laser sheet enters the combustor through the large front window and the camera/intensifier setup is rotated 30 degrees to image the LIF signal, also through the front window. The periscope laser alignment that is used in the PIV measurements results in too much attenuation of UV laser light through the products of the flame for sufficient signal at the base of the flame (in the proximity of \( x/D = 0 \)). The results of the azimuthal modal decomposition indicate that the flow is relatively axisymmetric from \( x/D = 0 \) to \( x/D = 1 \) and \( r/D = 0 \) to \( r/D = 0.75 \), the region of interest in the OH-PLIF measurements. As a result, we are able to compare the measurements in the PIV plane and the 30-degree offset PLIF plane with reasonable confidence.

**Comparison of the Two Facilities**

Both facilities consist of swirling premixed flames stabilized on shear layers. It is well known that variations in the heat release rate in such flames originate from large-scale disturbances to the shear layers. This means that the flame and flow response can be expected to be qualitatively similar in
these two experiments. Specifically, the response of the flow and the flame to various acoustic fields shows some consistency despite changes in combustor configuration. The physical characteristics of both the combustor facilities and flow fields are compared in Table 1.

Table 1. Comparison of flow and geometric parameters between the annular model combustor and the transverse forcing rig.

<table>
<thead>
<tr>
<th></th>
<th>Annular Combustor</th>
<th>Transverse Forcing Rig</th>
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<tr>
<td><strong>Flow parameters</strong></td>
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<tr>
<td>Reynolds number</td>
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<td>Flow velocity</td>
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<tr>
<td>Dump ratio</td>
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<td>7.3</td>
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<td>Nozzle inner diameter</td>
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<td>2.2 cm</td>
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<tr>
<td>Nozzle outer diameter</td>
<td>1.9 cm</td>
<td>3.2 cm</td>
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<td>Downstream length</td>
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<td>Circumference/Transverse Length</td>
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<td>Nozzle cavity length</td>
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<td><strong>Acoustic parameters</strong></td>
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<tr>
<td>Nozzle compactness (λ/D)</td>
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Several features of the two experiments match well, while others do not. The flow features are comparable between the two combustors. The Reynolds numbers are similar and the swirl number of the nozzles indicates that both flow fields are in the subcritical swirl flow regime. This means that both flows contain a large recirculation zone along the centerline that most likely extends upstream to the surface of the bluff body. This recirculation zone shape has significant implications for the flow dynamics, as is discussed at length by O’Connor and Lieuwen [45].

The geometric features of the two experiments in the region of the flame differ slightly. One important feature is the dump ratio, or the ratio of the area around the nozzle on the dump plane to the exit area of the nozzle. This parameter controls the extent of the expansion of the flow as it exits the nozzle and can have an effect on flame structure as well [46, 47]. It is for this reason that the transverse forcing rig was designed as a high aspect ratio combustor, in order to realistically mimic the dump ratios and wall boundary conditions that are found in annular combustors. The dump ratio in these two experiments is on the same order or magnitude, although it does not match exactly.

The instability frequencies noted in Table 1 indicate the transverse mode frequency present in each of these studies. In the case of the annular model combustor, the 1720 Hz tone is self-excited; in the transverse forcing experiment, the 1200 Hz tone is produced via open-loop forcing. Although the frequencies differ by 500 Hz between the two experiments, the compactness of the nozzles with respect to the acoustic wavelengths is similar. The ratio of the acoustic wavelength to the outer diameter of the nozzle (λ/D) of the annular model combustor is approximately 10.4 (with a sound speed of 340 m/s), while the ratio for the transverse forcing rig is 8.8. In both cases, the nozzle is sufficiently acoustically compact as compared to the acoustic wavelengths. This has important implications for the transverse to longitudinal coupling mechanism that drives the longitudinal flow oscillations in an in-phase forcing configuration. In both cases, the acoustic fluctuation of the pressure anti-node forces the nozzle in a relatively uniform manner, resulting in longitudinal acoustic fluctuations that drive the flame response at this condition.

Figure 5 shows the time-average flame shapes from both experimental configurations, as measured by OH-PLIF imaging. The main difference between the two cases is that the flame is anchored along both inner and outer shear layers in the annular rig but only the inner shear layer in the transverse forcing experiment. In both cases, the development of the turbulent flame brush is visible. The presence of neighboring flames in the annular combustor results in flame merging around x/D = 0.3, causing the larger curvature of the mean flame. The presence of flame on the outer shear layer results from the use of ethylene, rather than methane, as fuel as well as the presence of adjacent flames [43, 44]. In the transverse forcing rig, the flame is imaged approximately 0.65 cm from the dump plane due to the presence of a window frame that blocks the view of the nozzle exit.

Figure 5. Time-average flame shapes (from OH-PLIF imaging) for the annular model combustor (left) at \( u_o=18 \) m/s, \( S=1.2 \), and \( \varphi=0.85 \) and the transverse forcing rig (right) at \( u_o=10 \) m/s, \( S=0.85 \), and \( \varphi=0.9 \).

Another study by Fanaca et al. [48] has investigated the differences between an annular and a single-nozzle experiment, where the authors noted the differences in flow field between these two configurations. The critical difference noted in these experiments was the change in confinement between the single-nozzle combustor and the annular combustor, and a scaling was proposed for accounting for these differences in the flame transfer function results. This issue is not expected to arise in the current investigation due to the high-aspect-ratio geometry of the transverse forcing rig, which is similar to that of the annular combustor. The validity of comparing these two
experiments is discussed in the relevant sections throughout the paper.

RESULTS

The results of this study are presented in three sections. First, an overview of the self-excited standing wave instability is provided as a baseline for the more detailed flame and flow results. The behavior of the flame dynamics and the flow at the pressure node and anti-node is then compared and contrasted for both the annular combustor and transverse rig. Several important features of the flame dynamics are found to be consistent in both experiments, indicating that the velocity-coupling mechanisms and flame dynamics in the transverse forcing rig are more suitable than longitudinal forcing strategies for capturing the behavior of circumferential modes in annular combustion chambers. Finally, a framework for comparison of the two experiments is discussed.

Annular Combustor – Standing Wave

The spectral response of the instability in the annular combustor can be characterized from both pressure and the overhead OH* measurements. The high-speed OH* measurements are integrated at three injector locations to produce a global measurement of the heat release fluctuations suitable for spectral analysis. This is done by applying an image mask to isolate the response at each individual injector. Figure 6 shows spectra from both the pressure and heat release measurements, showing a self-excited azimuthal instability at a frequency of approximately 1720Hz.

![Figure 6. Pressure (top) and heat release (bottom) spectra for the full annular rig during a self-excited, standing wave instability, at $u_o=18$ m/s, $S=1.2$, and $\phi=0.85$.](image)

A short time-series is shown in Figure 7, in which the pressure fluctuations at the three locations around the annulus are plotted. The fluctuations are all either in-phase or out-of-phase with each other, with amplitude differences in the response at the three locations; this response is characteristic of a standing wave oscillation mode.

![Figure 7. Time-series of pressure oscillations at three locations around the annulus in the annular model combustor, at $u_o=18$ m/s, $S=1.2$, and $\phi=0.85$.](image)

A phase-averaged sequence of a self-excited standing-wave circumferential instability in the annular combustor (viewed from overhead) is shown in Figure 8. Although the mode is predominantly standing, the amplitude threshold for this case is $A+/A- = 1.7521$ which is close to the CCW spinning wave threshold of $A+/A- > 2$. Consequently there is a noticeable spinning component to the heat release fluctuations in the sequence.

The pressure nodes are approximately located at 12 o’clock and 6 o’clock positions whereas the anti-nodes are at 3 and 9 o’clock. The flames at the pressure anti-nodes see the largest fluctuations in heat release rate and can be easily observed when comparing 0 and 200 degrees. Throughout the cycle, the 18 flame configuration results in large-scale interaction of the fluctuating heat release along the outer annular wall and in-between flames. The spinning components can be observed by rotation of the merged heat release fluctuations around the annulus over the cycle.
Figure 8. Standing wave mode in the annular model combustor, visualized from the overhead mirror.

Pressure Anti-node Flame Behavior

As discussed in the Introduction, the pressure anti-node produces a symmetric acoustic forcing condition for the nozzles present at this location in the acoustic field. In a standing wave, the pressure anti-node corresponds to an acoustic velocity node, meaning that the acoustic velocity fluctuations will be symmetric about the centerline. This has been shown to result in a symmetric response from both the flame and the flow field.

Figure 9. Phase-averaged flame edges from OH-PLIF imaging at a pressure anti-node at $u_\infty=18$ m/s, $S=1.2$, and $\varphi=0.85$ in the annular model combustor. White arrows indicate location of symmetric vortex shedding.

Figure 9 shows the phase-averaged OH-PLIF images of the flame near a pressure anti-node location in the annular model combustor at the self-excited frequency of 1721Hz. At the anti-node, pressure fluctuations induce harmonic velocity oscillations in the inlet duct that cause the shear layers to start to roll-up close to the jet exit. This is illustrated by the large-scale wrinkling of the flame fronts stabilized on the inner and
outer shear layers over the oscillation cycle. Two concentric vortex rings form, which in the plane of the laser appear as two counter-rotating vortex pairs that are advected downstream with the mean flow. The process is denoted by the white arrows in Figure 9. In the absence of a significant transverse velocity fluctuation, the formation of these structures occurs in a symmetric fashion with no appreciable phase lag between the left and right hand sides of the flame. This axisymmetric response is similar to the response of single axisymmetric flames subjected to longitudinal forcing [44]. In this case, small deviations away from symmetry mainly arise from the anti-node not being positioned exactly at the center of the flame. Since the mode is self-excited, the node and anti-node locations are self-arranging.

Despite differences in the experimental setup, similar flame behavior is observed in the transverse forcing rig when subjected to symmetric acoustic forcing to simulate a pressure anti-node. Figure 10 shows a phase-averaged sequence of OH-PLIF images to illustrate this.

![Figure 10. Phase-averaged flame edges from OH-PLIF imaging at a pressure anti-node in the transverse forcing rig at 1200 Hz in-phase forcing and \( u_o=10 \text{ m/s, } S=0.85, \text{ and } \phi=0.9 \). White arrows indicate location of symmetric vortex shedding.](image)

Since the flame is not stabilized on both shear layers the wrinkling of the flame induced by the velocity oscillations at the nozzle inlet makes them less pronounced than those for the annular combustor. Nevertheless, the evolution of symmetric flame wrinkling is observed by tracking the white arrows through the image sequence.

Another way to see the symmetric response of the flame at the pressure anti-node is to examine the fluctuating vorticity field. The phase-averaged vorticity fluctuations under symmetric forcing conditions to simulate a pressure anti-node are shown in Figure 11.

![Figure 11. Phase-averaged vorticity fluctuation for the 1200 Hz in-phase forcing case at \( u_o=10 \text{ m/s, } S=0.85, \text{ and } \phi=0.9 \). Vorticity fluctuation is normalized by the bulk flow velocity divided by the annular gap width.](image)

These images show that unsteadiness in the annular jet is dominated by well-ordered vorticity fluctuations along the shear layer typical of the formation of vortex structures. The important feature of the fluctuating vorticity field is that the vorticity fluctuations are spatially in phase, but have opposite sign, emphasizing the symmetric nature of the disturbances in the velocity field.
Better spatial resolution and further analysis is needed to examine the structure of the fluctuating vorticity field in more detail and is the subject of ongoing work. However, it is worth drawing attention to the fact that the size and location where vortex structures begin to roll-up along a shear layer exhibit a hyperbolic dependence with amplitude of the velocity oscillations at the nozzle exit and the excitation frequency, see references [15, 49] for more details.

Considering the phase information provided by the fluctuating vorticity field provides further insight. The shear layer locations, both for the inner and outer shear layers on the left and right sides, is estimated from the time-average vorticity magnitude. At each downstream location along the shear layer paths, the phase of the FFT at the forcing frequency is calculated, unwrapped, and plotted in Figure 12. In this figure, the blue circles indicate the phase of the vorticity fluctuations along the inner shear layer (SL) and the green squares indicate the phase along the outer shear layer. The axes are the phases of the vorticity fluctuations along the left-hand side (ordinate) and the right-hand side (abscissa) in units of radians/pi. The solid black line indicates the path these phases would take if both sides were in phase. The dashed black line indicates the path these phases if both sides were out of phase. The black arrow indicates the downstream direction; this is congruent with the typical phase roll-off one would expect to see along a path with convecting disturbances.

Figure 12. Phase between left and right shear layer (SL) vorticity fluctuations at \( f_s = 1200 \) Hz for the 1200 Hz in-phase forcing case at \( u_o = 10 \) m/s, \( S = 0.85 \), and \( \phi = 0.9 \) in units of radians/pi. The solid line depicts equal phase and the dashed line depicts 180° out-of-phase behavior.

The results in Figure 12 indicate that the vorticity fluctuations in both the inner and outer shear layers cluster around the out-of-phase line, which is to be expected for this forcing condition. The 180° phase difference between the left and right sides of the shear layers is a result of the opposite sign vorticity. The resulting symmetric flame fluctuations are clearly visible in the data from both the annular and transverse-forcing combustors.

The longitudinal, symmetric velocity fluctuations at the pressure anti-node are driven by the coupling between the transverse acoustic field and longitudinal mass-flow fluctuations in the nozzle, through the transverse to longitudinal coupling mechanism. Both the velocity fluctuations and resultant flame fluctuations are relatively weak as compared to their asymmetric counterparts, presented in the next section, because of the low gain of the coupling process between the transverse acoustics and the longitudinal fluctuations. As is discussed by O’Connor and coworkers [33, 34], the strength of this coupling is frequency dependent as a function of proximity to the acoustic resonance in nozzle cavity. In the transverse forcing rig, the resonant frequency of the nozzle cavity is approximately 1800 Hz, far from the 1200 Hz forcing frequency considered in this study. However, 1800 Hz forcing data was not available for analysis at flow conditions similar to that of the annular model combustor.

**Pressure Node Flame Behavior**

The pressure node corresponds to a velocity anti-node in the standing acoustic mode. Here, the pressure fluctuations reach a minimum but the corresponding velocity fluctuations are asymmetric about the centerline and excite an asymmetric response in the flow field and the flame.
Figure 13 shows the phase-averaged flame motion at the pressure node in the annular model combustor. In comparison with the pressure anti-node response, the flame dynamics at the pressure node location show significant asymmetries. In the absence of large pressure fluctuations, the longitudinal velocity fluctuations induced in the inlet duct are small. However, the effect of transverse velocity fluctuations causes the shear layers, and hence the flame, to flap violently creating an observable phase difference between left and right hand sides. This phase difference can be estimated by comparing the left and right hand sides of the flame at times in the cycle. Comparing the right hand side of the flame at $\theta=0^\circ$ and the left hand side of the flame at $\theta=200^\circ$ shows qualitatively similar flame structures at similar downstream distances, implying the response of the two sides is in approximate anti-phase.

Similar flame dynamics are seen at the pressure node in the transverse forcing rig, as is shown in Figure 14. Here, the flame wrinkling is clearly asymmetric and much stronger than in the in-phase forcing case, for reasons discussed above. The asymmetric forcing results in asymmetric disturbances within the inner shear layer, leading to alternating flame wrinkles on either side of the flame in the plane of the laser.

The driving mechanism for the asymmetric motion in the flame is the helical vortex rollup in the shear layers. In a plane of the flow, this vortex rollup looks like alternate vortices shedding from the dump plane on either side of the centerline.
of the flow. This asymmetry about the centerline is visible in the phase-averaged vorticity fluctuation contours measured at this condition, shown in Figure 15.

![Vorticity Contours](image)

**Figure 15.** Phase-averaged vorticity fluctuation for the 1200 Hz out-of-phase forcing case at $u_o=10$ m/s, $S=0.85$, $\varphi=0.9$. Vorticity fluctuation is normalized by the bulk flow velocity divided by the annular gap width.

The asymmetry of the flow field is visible in the vorticity contours on either side of the centerline, keeping in mind the 180° offset that arises from the differences in sign of vorticity on either side of the centerline. At 43° in Figure 15, a section of the helical vortex is shed in the inner left shear layer. This structure then convects downstream and the separation point of the helical disturbances rotates around the circumference of the centerbody. Separation of the helical vortex can be seen on the right-hand side at 216° before the structure is similarly convected downstream. Evidence of the helical nature of this vortex shedding is described in Ref. [42], where an azimuthal modal decomposition showed that asymmetric vortex shedding, such as that shown in Figure 15, was the result of an $m=-1$ mode in the shear layers.

The phase difference between the vorticity disturbances on either side of the shear layers is plotted in Figure 16. Like the results discussed above in Figure 12, one must take into account the 180° phase shift that is introduced by the opposite signs of the vorticity on either side of the centerline.

![Phase Difference Plot](image)

**Figure 16.** Phase between left and right shear layer (SL) vorticity fluctuations at $f_o=1200$ Hz for the 1200 Hz out-of-phase forcing case at $u_o=10$ m/s, $S=0.85$, and $\varphi=0.9$ in units of radians/pi. The solid lines depict equal phase and the dashed line depicts 180° out-of-phase behavior.

Taking into account the 180° offset, it is clear that the vorticity disturbances at the forcing frequency in both the inner and outer shear layers are out-of-phase, as is to be expected at an asymmetry forcing condition.

An interesting observation seen in the vorticity phase results in both the in-phase and out-of-phase forcing cases is the phase “jump” that occurs between lines of constant phase difference. For example, the phase difference in the inner shear layer jumps from one solid line to another at $x/D=0.5$ in the out-of-phase forcing case shown in Figure 16. A similar jump is seen in the outer shear layer in the in-phase forcing case in Figure 12 at approximately the same downstream location. Similar jumps in phase along shear layers has been reported in Ref. [50].

**Comparison between Flame Dynamics in the Annular Combustor and Transverse Rig**

Despite the differences in flame structure between the two experiments, the symmetry of the flame dynamics in each of these rigs is similar for both the pressure anti-node and node conditions. At the pressure anti-node, symmetric fluctuations in the flame were observed in both flames, and these stem from ring vortices that are shed in both the inner and outer shear layers. Here, the coupling between the transverse acoustics in the combustor and longitudinal acoustics in the nozzle drive
this ring vortex shedding. In the transverse forcing rig, the amplitude of the flame response at this condition is less than in the out-of-phase forcing case due to inefficiencies in the transverse to longitudinal coupling mechanism away from the nozzle resonant frequency.

At the pressure node, violent asymmetric motion was observed in the flames in both experiments. Large flame wrinkles appear on alternate sides of the flame in the plane of the laser as a result of helical vortex shedding in the inner and outer shear layers. This asymmetric vorticity field was clearly shown in the phase-averaged PIV data.

Importantly, the symmetric and asymmetric response of the annular flames at the pressure anti-node and node locations is consistent with the symmetric and asymmetric velocity and vorticity response of the single transverse forced flame. This suggests that a single transverse forced flame can capture important flame dynamics associated with self-excited azimuthal instabilities. However, differences due to the presence of flame front merging in the case of the closely spaced annular flames may not be accurately captured by studying the response of a single flame; two or more flames are required to accurately capture the merged flame dynamics.

There are several key considerations in comparing these two types of experiments:

- Flow field – The “macro” geometry and behavior of the flow field should be similar between to experiments. In particular, the structure of the vortex breakdown bubble and the size and proximity of the shear layers play important roles in the dynamics response of the flow, and hence the flame. The similarity between the swirl numbers, dump ratios, and Reynolds numbers in these two experiments meant that the flow behavior would be similar in each case.

- Flame shape – Flame shape is important for determining the important velocity-coupling mechanisms present during the transverse instability. Here, both flames were anchored in the inner shear layer and vortex shedding in that shear layer determined much of the dynamical response of the flames at both acoustic forcing conditions. However, the flame in the annular rig was also anchored in the outer shear layer, and as such, the effects of outer shear layer vortex structures were not captured in the transverse forcing rig.

- Single versus multiple flames – Flame interaction may be an important and highly nonlinear source of flame heat release rate fluctuation in velocity-coupled combustion instability. In the annular model combustor, some level of flame interaction was present, meaning that the global heat release fluctuation level may be different from that of a single-flame combustor. As a result, direct comparison between multi-flame and single-flame flame transfer functions is not advisable. Despite that, the major velocity-coupling mechanisms that are measured in a single-flame experiment may still be pertinent to a multi-flame experiment, particularly in the portion of the flame upstream of the interaction.

- Acoustic frequencies and resonances – The transverse to longitudinal coupling mechanism has been shown in both experiment and LES to be an important driver of flame fluctuation, particularly at the pressure anti-node. The gain of this coupling is determined by the matching of the frequency of the acoustic mode in the combustor and the resonant frequency of the nozzle. While not possible in this study, care should be taken to match both combustor instability frequency and nozzle acoustics for similar flame response amplitudes at the pressure anti-node.

CONCLUSIONS

Several key conclusions have been reached in this comparison study of the dynamics in an annular model combustor and a transverse forcing rig.

1. Flame behavior during a self-excited, standing-wave instability in an annular model combustor is fundamentally similar to that in a transverse rig forced with a standing-wave pattern. Flame dynamics between the pressure node and anti-node are qualitatively similar in these two experiments. This validates the use of transverse rigs for investigation of azimuthal instabilities in annular gas turbine combustors.

2. The symmetry of the standing-wave acoustic field drives the symmetry of the flow and flame response. At the pressure anti-node, a symmetric forcing condition, flame fluctuations are symmetric as a result of symmetric vortex ring shedding the shear layers. At the pressure node, an asymmetric forcing condition, flame fluctuations are asymmetric as a result of a helical vortex ring in the shear layers.

3. Several key considerations are discussed for comparing the results from a transverse forcing rig to a full annular combustor. Matching of macro-features of the flow field, flames shapes, flame interaction levels, and acoustic conditions are important for accurate comparisons between these two types of experiments.

ACKNOWLEDGMENTS

The work at Georgia Tech has been partially supported by the US Department of Energy under contracts DEFG26-07NT43069 and DE-NT0005054, contract monitors Mark Freeman and Richard Wenglarz, respectively.
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