Helical Flow Disturbances in a Multinozzle Combustor

This paper describes an experimental investigation of a transversely forced, swirl stabilized combustor. Its objective is to compare the unsteady flow structures in single and triple nozzle combustors and determine how well a single nozzle configuration emulates the characteristics of a multinozzle one. The experiment consists of a series of velocity field measurements captured on planes normal to the jet axis. As expected, there are differences between the single and triple nozzle flow fields, but the differences are not large in the regions upstream of the jet merging zone. Direct comparisons of the time-averaged flow fields reveal a higher degree of nonaxisymmetry for the flow fields of nozzles in a multinozzle configuration. Azimuthal decompositions of the velocity fields show that the transverse acoustic forcing has an important influence on the dynamics, but that the single and multinozzle configurations have similar forced response dynamics near the dump plane. Specifically, the axial dependence of the amplitude in the highest energy axisymmetric and helical flow structures is quite similar in the two configurations.

The larger objective of this work is to understand the scaling between the single and triple nozzle combustors and determine how well a single nozzle configuration emulates the multinozzle combustor. Its objective is to compare the unsteady flow structures encountered in the multinozzle configuration as well.

The analysis addresses the question “to what extent does the single nozzle configuration emulate the multinozzle configuration? This question is part of a broader issue facing industry and multinozzle configurations have similar forced response dynamics near the dump plane. Specifically, the axial dependence of the amplitude in the highest energy axisymmetric and helical flow structures is quite similar in the two configurations. Thus, upstream of the jet merging zone, the hydrodynamic influence of one swirling jet on the other is minimal. As such, that jet–jet interactions in this configuration do not have a significant influence on the unsteady flow structures.

\[ \dot{B}_m(r, z, \alpha) = \frac{1}{2\pi} \int_0^{2\pi} e^{-im\alpha} \tilde{u}_j(r, \theta, z, \alpha) d\theta \]  

(2)

The coefficients, \( \dot{B}_m \), capture the radial dependence of a spatial pattern of fluctuations of the \( j \)th velocity component for each mode, \( m \).

The larger objective of this work is to understand the scaling for how the unsteady heat release responds to flow disturbances. To illustrate, within a linear context, we can write the unsteady heat release as

\[ \frac{Q'}{Q} = \sum_m F(m) \frac{u'_m}{u} \]  

(3)

where \( \dot{B}_m \) is referred to as the helical mode coefficient. The HMD is performed by solving for the HMD coefficients, by numerically spatially integrating the velocity field according to the following equation:

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pattern of flow disturbances, quantified by the transfer function $F(m)$. In a recent paper, Acharya et al. showed that that $F(m) = 0$ for $m \neq 0$ in an axisymmetric mean flow [2]—i.e., only the $m = 0$ mode contributes to global heat release fluctuations. While other helical modes lead to local flame wrinkling and heat release, their spatially integrated effects cancel. It is only through the presence of axisymmetric flow disturbances that the potential effects of helical modes can influence the global heat release [3]. Another important influence, then, of nozzle–nozzle interactions is to induce nonaxisymmetry into the flow field and flame.

A number of measurements of either the self-excited or forced response characteristics of single nozzle, swirl flames have been reported [4–9]. These measurements generally illustrate the strong presence of axisymmetric and helical vortices that distort the flame. Moreover, the nature of the excitation can change which modes are most strongly excited, as shown in the transverse forcing experiments of Zhang et al. [10] or the self-excited measurements of Worth and Dawson [11,12]. Specifically, O'Connor showed that the dominant azimuthal flow disturbance, parameterized by the mode number $m$ (see Eqs. (1) and (2)), depended strongly upon whether the nozzle was located at a pressure node/velocity antinode or vice versa. For example, O'Connor’s results showed that when the acoustic mode is configured with a pressure antinode at the nozzle, the $m = 0$ mode (characterized by axisymmetric vortex rings) was the dominant mode of flow response. In contrast, when the acoustic mode was configured with a transverse velocity antinode at the nozzle, the dominant response was an $m = 1$ mode (characterized by a single helical vortex tube).

Recently, a number of multinozzle measurements and computations have become available. Santavicca and coworkers [13] reported results for a five-nozzle configuration located within a larger circular combustor, and has extensively compared the resulting flame transfer functions to those obtained in a single nozzle configuration. Significant conclusions from their work are that, first, the flame shapes can become strongly distorted from their nominally circular shape due to flame–flame and flame–wall interactions. Second, the time-averaged flame lengths change. However, the measured transfer functions of the longitudinally excited flames are quite similar to those of a single nozzle, when the change in flame length in the multinozzle configuration is corrected for in the dimensionless frequency, $f_{T} = C_{22}/U_{t}$. Several multinozzle annular results are also available. For example, Poinset and coworkers [14] presents computations of self-excited oscillations in an annular combustor with 15 equally spaced nozzles. Their results show that the nozzle response depends on its location in the acoustic field, and therefore axisymmetric location in the annulus. Similarly, Worth and Dawson [11,12] presented results from an annular combustor, showing that the flame response varies strongly around the annulus, depending upon the nozzles’ positions in the standing wave field. Their results show many similarities to the single nozzle measurements of O’Connor et al. [15], such as indications that some flames are dominantly excited by helical disturbances and some by axisymmetric disturbances. Additionally, Worth and Dawson have investigated the flame interaction regions in multinozzle swirling [12] and nonswirling [16] combustors, showing that complicated flame dynamics occur downstream of the flame interaction region.

Bourgin et al. [17] performed experiments on a full annular rig, with 16 nozzles and quartz inner and outer walls. They also demonstrated that transverse instabilities cause the individual nozzles to respond differently. For example, a transverse instability can be manifested as a spinning wave, so that the individual nozzle response is at a phase delay that spins around the annulus. In contrast, a longitudinal instability forces the nozzles to respond with synchronous phase.

Our specific focus in this paper is on the unsteady flow structures in swirling flows, and to what extent the space–time evolutions of the dominant disturbance modes in a single and multinozzle burner compare with each other. At axial locations far enough downstream where the jets in a multinozzle configuration physically merge with each other, it seems fairly clear that there must be differences. However, we are also interested in cases where the jets do not merge, or in comparing the flow dynamics at upstream locations before they merge. There is good reason to believe that even in the latter cases, the multinozzle system can differ materially from the single nozzle system, as outlined next.

The hydrodynamic stability of shear flows is dominated by the distribution of vorticity in the flow, and the mutual self-induction that one vortical element induces on another. For this reason, the hydrodynamic stability characteristics of a single shear layer, and that of two shear layers placed next to each other (i.e., a wake or a jet), are materially different from each other. Similarly, the hydrodynamic stability of a single jet or wake flow, and that of multiple jets or wakes, can profoundly differ. A variety of studies of multinozzle jet flows bears this out. It is well known that side-by-side jets are “attracted” toward each other and that the jets bend toward the centerline and merge into a single jet [18]. Moreover, two jets placed side-by-side exhibit dynamics that do not occur when they are in isolation. For example, Bundred and Smith [19] studied parallel planar jets located $7 \leq s/D \leq 25$ apart from each other, showing that they exhibit a sinuous “flapping” instability associated with a global instability whose frequency is a function of jet spacing and the jet momentum flux ratio. Green and Crighton [20] performed stability analyses of two interacting round jets, where they formulated their analyses to describe the dynamical displacement of the jet/ambient fluid interface. They define four distinct instability modes. These modes are differentiated, first, by their symmetry/antisymmetry about the geometric plane of symmetry between the jets. A sinuous mode involves an antisymmetric flapping of the jets across the plane of symmetry, and an out-of-sync flapping parallel to the plane. A varicose mode manifests as a symmetric motion about the plane of symmetry, and the two jets uniformly flapping in the same direction parallel to the plane. In addition to the relative motion of the jets, the individual jets themselves may exhibit symmetric or antisymmetric dynamics. They found that at closer separation distances, the varicose modes dominated the sinuous modes (which become stabilized at close separations). Their results were qualitatively similar for planar jets.

Another relevant study was performed by Ko and Lau [21], who reported hotwire experiments on two planar jets whose centers were separated by approximately $s = 2.5D$. Their measurements showed that significant Reynolds stresses were absent near the line of symmetry between the jets until more than $1.7D$ downstream of the dump plane. For that jet spacing, they showed that fluid dynamics near the dump plane resembled the simple shear layers of the individual jets, suggesting that the coherent structures generated by jet–jet interaction do not appear until further downstream.

This paper presents a study of interacting, reacting, swirling jets. It focuses on axial positions near the dump plane, upstream of $z/D \approx 1$ where the shear layers from neighboring jets merge. At these upstream axial positions, it is unclear what hydrodynamic influence, if any, the jets have on each other. The primary objective of this study is to identify which hydrodynamic mode dominates the response to each of the three forcing configurations (unforced, in-phase, and out-of-phase), and to determine if this result is the same in a single nozzle configuration as in a triple nozzle configuration. In particular, our aim is to determine whether the dominant hydrodynamic modes are materially different, such as suggested by several of the above referenced studies.

Experimental Facility

The experimental facility shown in Fig. 1(a) was designed to simulate acoustic fluctuations in annular combustion chambers with an “unwrapped” sector of the annulus. The facility is detailed in previous work [22,23], and its key features are...
summarized here. The internal dimensions of the combustor are 1.14 m × 0.10 m × 0.34 m where the longest dimension is along the direction of forced transverse acoustic excitation. The top of the combustor enables optical access through a rectangular quartz window 0.2 m × 0.09 m, while allowing exhaust gases to pass through 0.08 m diameter ports on either side of the optical window. Two large quartz windows, referred to as the main windows, allow optical access to the flow field through a 0.27 m × 0.27 m viewing area.

The facility is capable of housing multiple nozzle configurations. In “single nozzle” mode, the center nozzle is fitted with a swirler and the outer two nozzles are blanked off. In “triple nozzle” mode, all three nozzles are fitted with swirlers, which are fed from a common plenum. The air is preheated to 400 K and enters the combustor through an insulated settling section and conditioning chamber. The air enters the combustion chamber through either a single or three dual-annular, counter-rotating swirler premixers [24–26] with geometric swirl numbers of approximately \( S = 0.62 \). The fully premixed flow is fueled in the swirlers with natural gas at an equivalence ratio of 0.95, and is mixed by counterswirl. The nozzle diameter, \( D \), is 32 mm, and in triple nozzle configuration, nozzles are spaced 99 mm (3.1D) apart, from center-to-center. The nominal nozzle exit velocity, \( u_n \), of this atmospheric facility is 25 m/s, corresponding to \( Re = 30,600 \) based on the outer diameter of one premixer. The nominal velocity is defined as the bulk velocity exiting the swirler, based on the premix mass flow rate, the nozzle area, and the flow density.

Acoustic Excitation

The combustor has three 100 W Galls speakers on each side and each set can be independently driven. The speakers are connected to the ends of adjustable tubes, seen on the side of the facility in Fig. 1(a). By changing the phase between the sets of speakers, the transverse acoustic field can exhibit modal patterns ranging from standing to traveling waves. All forced cases were excited with a transverse acoustic velocity amplitude of approximately 10% of the nominal nozzle exit velocity.

This study explores three different transverse acoustic forcing configurations: unforced, in-phase forcing, and out-of-phase forcing. During in-phase forcing, the speakers are driven at the same phase. This generates an acoustic pressure antinode and velocity node at the nozzle centerline. Similarly, during out-of-phase forcing the speakers are driven with a 180 deg offset. This generates an acoustic pressure node and an acoustic velocity antinode at the nozzle centerline. These acoustic fields were verified by acoustic pressure measurements under nonreacting, nonflowing conditions, and further detailed in Ref. [22].

Diagnostics

Measurements of the velocity field were recorded through the main front window using high speed particle image velocimetry (PIV). Seeded image pairs were obtained with a 10 kHz PIV system, using a Litron Lasers Ltd. LDY303He Nd:YLF laser with a wavelength of 527 nm and 5 ml/pulse pulse energy. Aluminum oxide particles, nominally 1–2 \( \mu \)m in diameter, were introduced to the preheated air flow upstream of the settling chamber to ensure uniform particle mixing. A LaVision divergent sheet optic, with an \( f = -10 \) mm cylindrical lens, created a 1 mm thick laser sheet.

The illuminated particles were imaged with a Photron High-Speed Star SA1.1 camera at 10,000 frames per second, with 704 × 400 pixel resolution. Each PIV data set consisted of 10,000 image pairs that were acquired with a separation time of 20 \( \mu \)s. The high sample rate and quantity of images provided a spectral frequency resolution of 1 Hz. The dominant spectral feature in the unforced data occurs at 170 Hz, and in the forced data at 400 Hz, so the 1 s of sampling time was sufficient to ensure good convergence in estimates of both time-averaged and unsteady quantities. The calculations for the velocity field were performed in DAVIS 7.2 software provided by LaVision. Vector fields were calculated on the background subtracted particle images using 50% overlapping interrogation windows, a first pass with 32 × 32 pixel windows and two more passes with 16 × 16 pixel windows. The resulting velocity field spatial resolution is about 0.8 mm/pixel. The nearly square measurement domain had a 102 × 102 mm field of view, corresponding to 3.2D × 3.2D. A threshold was set to remove vectors of greater than 40 m/s and spatial filtering was applied to vectors whose velocity was greater than three times the RMS velocity of the surrounding groups of vectors. The number of vectors removed by this scheme was, on average, 0.1% of the total number of vectors. Uncertainty analysis showed typical velocity uncertainties were 2–5% of the local mean.

Planar Mie scattering images captured for PIV are shown in Fig. 2. Jumps in seeding density are apparent. These jumps occur across the instantaneous flame, and at the interface between the cold, dense reactants and the hot, lower density products. The vortex breakdown stabilized flame surface is shown by the solid continuous curve, and demonstrates the significant nonaxisymmetry in the instantaneous flame and flow. This is due in part to turbulence, as well as the quasi-coherent fluid mechanic structures in the recirculating flow.

Data were acquired on each of two different measurement planes, in separate experiments. For measurements captured on the r–z plane, the sheet entered the combustor box through its top, passed along the z-axis (see Fig. 1(b)), and its plane was parallel to the main window planes. For measurements on the r–\( \theta \) plane, the laser sheet entered the combustor box through one of its main windows, and its plane was parallel to the dump plane. Experiments captured on the r–\( \theta \) plane were repeated at five different axial positions (see Fig. 3).

Results and Discussion

Next, we present typical results, with the aim of comparing the flow field differences between single nozzle and triple nozzle configurations. We begin by comparing the time-averaged flow fields for the two configurations. Next, we compare the unsteady flow structures. As detailed in the Introduction section, both the time
averaged and dynamic flow features have a direct influence on the spatially integrated unsteady heat release.

Time-Averaged Velocity Field Characteristics

Figure 3 illustrates the time-averaged, unforced flow field measured on an \( r-z \) plane. Spatial coordinates are nondimensionalized by the nozzle exit diameter, \( D \), and velocities are normalized by the nominal velocity, \( u = 25 \text{ m/s} \).

In the region downstream of the premixer exit, the flow approaches the bulk average velocity. As the flow proceeds downstream, it expands around the time average leading edge of the central recirculation zone or vortex breakdown bubble (VBB). The black line designates the points of zero axial velocity, and the bullseye represents the stagnation point. The axial positions of the \( r-\theta \) measurement planes are indicated on part (a).

Figure 4 shows a typical time-averaged velocity field acquired on a \( r-h \) measurement plane. This illustrates the swirl profile, and gives a qualitative feel for the spatial distribution of azimuthal and radial velocity on such planes. We next focus on more quantitative characterization of these data.

Figure 5 shows the radial dependence of the azimuthal and radial velocities for the triple nozzle rig, overlaid on those for the single nozzle rig (throughout this paper, triple nozzle data are reported for the center nozzle). The plots show the radial dependence of the average velocity at two azimuthal positions: 90 deg, which points toward the combustor wall (a viewing window), and 180 deg, which points toward a neighboring nozzle. Two different axial positions are shown, distinguished by color, with the darker curves closer to the dump plane. Single nozzle results are solid curves, and triple nozzle results are dashed curves. The overlays demonstrate the significant similarity between these time-averaged flows, with the most noticeable differences appearing at larger radial positions. A comparison of the 90 deg to the 180 deg data shows greater differences for the triple nozzle than for the single nozzle configuration, indicating a higher degree of axisymmetry in the time-averaged flow of the single nozzle.

The discussion around Fig. 5 shows the expected result that the time-averaged flow field of the single nozzle has a greater degree of axisymmetry than that of the triple nozzle configuration. This motivates Fig. 6, which shows polar plots of azimuthal velocity contours from measurements on \( r-\theta \) planes. These plots confirm the near axisymmetry of the single nozzle time-averaged flow, and illustrate the nonaxisymmetry of the triple nozzle flow. From the figure, it is evident that in the triple nozzle configuration, the swirling jet cross section becomes elongated, and "squeezed" between the walls (toward the top and bottom) and the neighboring nozzles (to the left and right). In addition, the major axis of this elongation is preferentially tilted along one of the two diagonal directions, which is repeatable for all triple nozzle tests. The direction of this tilt may be intuited when considering the clockwise swirl direction of the two neighboring nozzles, and their
induced velocity fields. For example, the right-hand nozzle pushes the top-right quadrant of the central jet up and to the right (stretching it), and pushes the lower-right quadrant up and to the left (compressing it). Likewise, the left nozzle pushes the upper left quadrant of the central nozzle down and to the right (compressing), and the lower left quadrant of the central nozzle down and to the left (stretching).

In general, the effect of forcing on the time-averaged flow is minimal and so no additional results are included. Illustrative data are presented in previous work, which shows that the VBB maintains its natural configuration even at high forcing amplitudes. However, acoustic forcing does have a significant influence on the flow dynamics. There, we next focus on the self-excited and forced response dynamics of the flow.

Unsteady Velocity Field Characteristics

The instantaneous flow field exhibits a substantially more complicated structure than its time average, as shown by the sequence of images in Fig. 7. The grayscale contours depict the magnitude of the axial velocity, where the lighter contours indicate higher velocity. Velocity vectors with high axial velocity pointed downstream are colored black, and those with low or reversed axial velocity are colored white.

In the figures, the bullseye marks the stagnation point in the time-averaged flow (due to vortex breakdown), which is nominally about 1.3D downstream of the dump plane. The star indicates the instantaneous stagnation point, which travels around the combustor and significantly varies its position from its time average. Visual inspection of a sequence of these images reveals some insight into the VBB motion. For example, apparent movement of the stagnation point in-and-out of plane, coupled with its reappearance on the opposite side of the flow centerline, indicates progression of the recirculating flow region about the flow centerline. These images call attention to the complexity of the instantaneous flow structure, and motivate the use of the HMD to better understand the spatial and temporal flame/flow dynamics. Furthermore, the in-and-out of plane motion apparent in Fig. 7 motivates a study of the azimuthal dependence of the flow dynamics.

The Fourier transformed velocities are decomposed into spatial modes using the HMD outlined in Eqs. (1) and (2). The azimuthal dependence of each mode is harmonic with periodic boundary conditions. A positive mode number, \( m \), indicates counter clockwise rotation as time advances, and the absolute value of \( m \) describes the number of azimuthal “periods” in the pattern. For example, Fig. 8(a) shows contours of \( \text{Re}\{B_{y,1}(r,z = 12 \text{ mm}, f = 400 \text{ Hz}) \exp(i \phi)\} \), which illustrates a “snapshot” in time of the \( m = 1 \) azimuthal velocity mode for a case with 400 Hz, in-phase forcing. This spatial pattern rotates uniformly in the clockwise direction at 400 Hz. Figure 8(b) shows a snapshot of the sum of the \( +1 \) and \( -1 \) modes; this pattern does not rotate rigidly, and instead evolves with time as the two counter-rotating modes are superimposed. The original velocity field may be exactly reconstructed by summing all modes (for all mode numbers and frequencies).

The radial dependence of the helical mode coefficients at the forcing frequency and a fixed azimuthal frequency is shown in Fig. 9. Two datasets are presented at nominally the same flow conditions, during two different testing campaigns. This comparison serves as a visual indication of the experimental repeatability. First, note the qualitative similarity between the two campaigns (solid and dashed lines). Also, note that the odd modes are nearly on top of each other, differing by approximately 10%. The even modes, such as the axisymmetric \( m = 0 \) mode, exhibit less repeatability. The strength of the \( m = 0 \) mode is strongly influenced by acoustic coupling with the nozzle/plenum system, and we speculate that these differences reflect subtle differences in temperature and flame location between the two tests. Although there is some quantitative variability between the two datasets, the goal of this paper is a qualitative identification of the dominant hydrodynamic

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mode, and Fig. 9 shows that the relative strengths and shapes of the modes are quite repeatable.

As Eq. (2) shows, the helical mode coefficients are functions of frequency, radial position, axial position, mode number, and velocity component. For presentation and comparison purposes, we reduce the number of dependencies of the helical mode coefficients by plotting their magnitudes only at the tonal forcing frequency, for forced cases. For unforced cases, the self-excited hydrodynamic oscillations generally spread their energy over a range of frequencies. For example, Fig. 10(a) shows the power spectrum of a helical mode coefficient at a fixed position in the combustor, with energy distributed across a narrow band of frequencies centered around 200 Hz. Therefore, for unforced cases, the HMD results are represented by the integrated spectral energy of $\hat{B}_{jm}$.

The radial dependence of the helical mode coefficients is removed by integrating the squared magnitude of the helical mode coefficients across the radial dimension, i.e.,

$$C_{jm}(x) = \int_{r} |\hat{B}_{jm}(r,x)|^2 r dr$$

The HMD results are summarized in Fig. 11, which shows the axial dependence of the azimuthal helical mode coefficients for several mode numbers. Results from the triple nozzle configuration are overlaid on those for the single nozzle configuration for three different forcing conditions: unforced, 400 Hz in-phase, and 400 Hz out-of-phase.

The figure makes two important points. First, the $m = 1$ mode dominates the unforced cases, the $m = 0$ mode dominates the in-phase forcing cases, and the $m = -1$ mode dominates the out of phase forcing cases. This shows that an axisymmetric hydrodynamic response is excited by in-phase forcing, which configures the acoustic mode with a pressure antinode at the nozzle. In contrast, a helical response is the dominant hydrodynamic response excited by out-of-phase forcing, which configures the acoustic field with a transverse velocity antinode at the nozzle. This result is consistent with the observations of O’Connor [27], who demonstrated that the dominant mode depends on the acoustic forcing configuration.

The second point is that the data consistently show the same dominant mode for the single nozzle and triple nozzle configurations. Likewise, the order of modal dominance and the axial dependence of the modes is the same between the single nozzle and triple nozzle configurations.
triple nozzle configurations. This is the key result of this study, and it shows no substantive differences between the energy in the different azimuthal modes between the single and triple nozzle.

The first of the above points is important from a combustion instability perspective because it shows that swirl stabilized combustors can have completely different hydrodynamic response depending on the nature of the acoustic mode, and the fact that the various nozzles in the combustor can have fundamentally different hydrodynamic responses based on where they are located with respect to the acoustic mode. The second point is important because it suggests that single nozzle combustors can capture the same near-dump-plane hydrodynamic response as multinozzle combustors, which adds merit to the study of simplified, single nozzle combustors.

The primary objective of this study was to identify which hydrodynamic mode dominates the response to each of three forcing configurations, and to determine if this result is the same in a single nozzle configuration as in a triple nozzle configuration. The results showed that the single and triple nozzle configurations have the same forced flow response characteristics. This important result is somewhat unexpected given the close spacing between the nozzles, relative to the spacings in nonswirling jets where significant changes in jet dynamics have been reported, as discussed in the Introduction section. Specifically, the nozzle spacings used in this study are $s/D = 3.1$, while significant interaction between 2D jets was found by the experiments of Bunderson and Smith [19] for $s/D$ values up to 27, and for round jets at $s/D$ values up to 10 by the stability analysis of Green and Crighton [20].

This is an important result that requires further, similar analysis from other experimental rigs. This work motivates two useful future studies. The first is an extension of this study to obtain similar comparison measurements further downstream, including...
regions where the jets and flames have clearly merged. Such measurements were not possible in this study due to seeding difficulties and optical setup.

The second useful future study is a similar comparison study of the unsteady heat release. Although the flow structures are similar in the single nozzle versus the triple nozzle configuration, it should be emphasized that the unsteady heat release may differ. As discussed in the context of Eq. (3), slight changes in axisymmetry in flows with strong helical modes, such as would be induced by nozzle–nozzle interaction, can materially alter the global heat release. However, in flows dominated by axisymmetric, $m = 0$, disturbances, this result does suggest strong similarities in the forced response characteristics of single and triple nozzle flows. This hypothesis is consistent with Santavicca’s data described in the Introduction section, who found very similar flame transfer functions between a single and five-nozzle rig, once the change in flame lengths were corrected for. This motivates an experimental study to measure the sensitivity of the unsteady heat release to single nozzle versus triple nozzle configuration.

Conclusion

This paper has presented velocity field measurements and analysis for a transversely forced, swirl stabilized combustor. The analysis compared single nozzle and multinozzle configurations. Previous studies of multiple jet flows indicate that neighboring jets mutually interact upstream of the direct shear layer merging, which can alter both the time-averaged and dynamical flow fields. Therefore, this experimental study has probed the velocity field near the dump plane to see if such mutual interactions exist.

Results show minor differences in the time-averaged flows when switching from single nozzle to multinozzle flows. The most notable difference is a nonaxisymmetric elongation of the jet cross section. The major axis of the elongation “tilts” to align itself away from the nearby combustor walls and nozzles. The direction of this tilting appears to be prescribed by the swirl direction of the neighboring nozzles.

The dynamics of the flow field are studied using a Fourier decomposition in time. Spatial mode shapes are constructed using an azimuthal decomposition. The analysis shows that the single nozzle and triple nozzle configurations have the same qualitative natural and forced flow response structures. Furthermore, these results corroborate previous work showing that the forced response structure of a given nozzle is highly dependent on its position along a standing acoustic mode (i.e., whether it is near a pressure or velocity antinode). Thus, the mutual interaction of swirling jets in this geometry has a slight influence on the time averaged flow field, and little influence on the natural or forced flow response dynamics.

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$r$</td>
<td>radial position</td>
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<tr>
<td>$R_v$</td>
<td>vortex ring radius</td>
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<tr>
<td>$s$</td>
<td>nozzle spacing, center-to-center</td>
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<tr>
<td>$u$</td>
<td>nominal time-averaged velocity</td>
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<tr>
<td>$u_{j0}$</td>
<td>$j$th velocity component</td>
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<tr>
<td>$u_{jn}$</td>
<td>$j$th velocity component of the $n$th helical mode</td>
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<tr>
<td>$\Gamma$</td>
<td>circulation</td>
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<tr>
<td>$\theta$</td>
<td>azimuthal position</td>
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<td>$\omega$</td>
<td>angular frequency</td>
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References


